Enhancing BMX Performance Using a Multidisciplinary Sport Science Approach

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Statement of Originality

I declare that this submission is my own work and to the best of my knowledge and belief contains no material previously published by another person except where due reference is made explicitly. This thesis describes original research conducted by the author at School of Health Sciences, University of Canterbury New Zealand from August 2017 to February 2021 and has not previously been submitted for a degree or diploma in any University. I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design, conception, presentation and linguistic expression is acknowledge.

A number of individuals have substantially contributed to the research presented in this thesis. Their contributions are as follows:

Dr. Carl Petersen	Research design and manuscripts review
Dr. Brad Miles	Research design and manuscripts review
Dr. Daniel Gahreman	Research design and manuscripts review
Dr. Majid Kouzehchian	Manuscript review (Study 5 only)
Prof. Beat Kentchle	Manuscript review (Study 2 only)

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Amin Daneshfar (Candidate)

Abstract

The sport of Bicycle Motocross (BMX) is an Olympic discipline. It is classified as off-road bicycle racing with an intermittent sprint nature due to the high number of repeated maximal efforts required. To improve riders' performance, practitioners often seek to identify the most important factors that contribute to winning a race. Current research has mainly focused on explosive starting ability and methods to generate and sustain maximal power, which have been deemed critical factors in BMX. However, data describing the physical and physiological demands, as well as ways of improving riders' performance, are still scarce. Using a multidisciplinary sport science approach, this thesis consists of five complimentary studies providing insight into the key performance factors of BMX racing and novel ways of enhancing riders' race performance.

The first laboratory study of this thesis focused on investigating the physical attributes of 15 sub-elite BMX riders and subsequently predicted the key performance indicators using correlation and multiple linear regression analyses. This study identified a model in which power-to-weight ratio (PWR), combined relative back-leg-chest strength, and arm span explained ~87% of the variability in BMX finish time.

It is important to identify the key peformance predictors in the laboratory condition and define the demands of a BMX rider (Study 1). However, measuring performance in the actual track, where riders usually race, would provide more details around the demands of a race and help coaches to design effective programmes. Therefore, due to the lack of scientific research on physiological characteristics of a BMX race, Study 2 was undertaken to analyse the physiological factors involved in a simulated race where riders perform multiple time trial in a day. Twelve male sub-elite BMX riders undertook a maximum aerobic capacity test in the laboratory and a week later, completed six laps on a BMX track, each interspersed with 15

min of passive recovery. This second study identified a significant correlation between PWR with lap time, however the strength of this association decreased with each subsequent lap. A strong contribution of the aerobic energy system during BMX racing was evident with mean $\dot{V}O_{2peak}$ greater than 80% of the laboratory measured $\dot{V}O_{2max}$. The mean blood lactate response (difference of pre and post value) was significantly associated with lap time and demonstrates the importance of the anaerobic glycolytic energy system contribution to BMX racing. Despite the relatively short period (30-40 % of time trial time) of pedalling during BMX racing, both aerobic and anaerobic energy systems are important contributors to lap performance.

Given the importance of power output in BMX racing highlighted by the first two studies, Study 3 was undertaken to investigate power production profile across the whole track circuit and correlated the power output during different track sections with overall time trial time. Fourteen male sub-elite BMX riders participated in this study and performed two laps with 15 min passive recovery between each lap. Lap time was significantly associated with time cornering (from start to the end of first corner). Having zero power values included (zero values reflect non-pedalling periods); the average power was ~ 28% of the peak power, compared to 62% when zero values were excluded. Race power output analysis may help BMX cyclists recognize the need to apply certain cadence strategies to maximise power production in certain sections of the BMX track, especially during the start and the first corner.

Having highlighted the importance of muscular power in BMX performance, it is important to explore strategies that could potentially improve power production. With this in mind, Study 4 assessed the effectiveness of a BMX specific Motor Imagery (MI) training program on time trial performance. To date, the transfer of MI has not been adequately evaluated in cycling specific settings. Using a crossover study, 13 sub-elite BMX riders (11 male, 2 female) undertook four weeks (80 min / week) of MI training, in addition to their normal BMX training. Pre and post MI training, physical testing was conducted which included assessing participants' vertical jump as well as, three BMX track time-trials. Despite no statistically significant improvement in riders' finish time following MI training in any of the three time trials, relative peak power significantly improved (~4 %) following MI practice compared to the baseline and control condition.

In addition to psychology strategies, athletes also use nutritional interventions to improve performance. In the fifth and final Study, the effects of pre-time trial caffeine supplementation on riders' performance was investigated. The effect of caffeine on anaerobic sprint performance, such as BMX racing is equivocal and requires further investigation. In a randomized, placebo-controlled, crossover design, 14 male BMX riders consumed either (300 mg; 4.2 ± 0.2 mg·kg^{-1}) caffeinated or a placebo gum, and undertook three BMX laps. Administering caffeine by chewing gum significantly improved simulated BMX time-trial performance by 1.5 %. This was most likely through improving riders' power production (3%) and/or reducing the perception of efforts (6.6 ± 1.3) compared to the placebo (7.2 ± 1.7) during laps.

Overall, using a multidisciplinary sport science approach, this thesis highlighted several physical and physiological factors that contribute to BMX performance. In particular, riders' anthropometry, muscular strength and explosive power, as well as having a highly developed aerobic capacity are especially important for BMX race performance. In addition, using a BMX specific motor imagery training improved riders' power production, but further research is required to identify its influence on race performance. Lastly, caffeine consumption has an ergogenic effect on BMX riders' overall time trial performance. BMX coaches and riders can utilise the outcomes of the current thesis and should consider using a multidisciplinary performance strategy when planning training programmes and considering talent identification and development.

Keywords: **BMX racing, sport physiology, sport nutrition, sport psychology, time trial, cognitive training**

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Please detail the nature and extent (%) of contribution by the candidate:

A. Daneshfar contributed to the research concept and study design, writing of the manuscript, literature review, data collection, and statistical analyses.
Overall 90%

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Amin Daneshfar, Carl J. Petersen & Daniel E. Gahreman (2021) The effect of 4 weeks motor imagery training on simulated BMX race performance, International Journal of Sport and Exercise Psychology, DOI: 10.1080/1612197X.2020.1869801

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Journal Publications

- **Daneshfar, A**., Petersen, C., Miles, B., & Gahreman, D. (2020). **Prediction of track performance in competitive BMX riders using laboratory measures**. *Journal of Science and Cycling*. doi: https://doi.org/10.28985/0620.jsc.06

- **Daneshfar, A**., Petersen, C., & Gahreman, D. (2020). **Power Analysis of Field-Based Bicycle Motor Cross (BMX)**. *Open Access Journal of Sports Medicine*. 2020: 113-121. doi: https://doi.org/10.2147/OAJSM.S256052

- **Daneshfar, A**., Petersen, C., & Gahreman, D. (2021). **Determinant Physiological Factors of Simulated BMX Race.** *European journal of sport science*. doi: https://doi.org/10.1080/17461391.2020.1859622

- **Daneshfar, A**., Petersen, C., & Gahreman, D. (2021). **The Effect of 4 Weeks Motor Imagery Training on Simulated BMX Race Performance.** *International Journal of Sport and Exercise Psychology*. doi: https://doi.org/10.1080/1612197X.2020.1869801

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Ethical Declaration

The University of Canterbury's Human Ethic Committee has approved all the studies related to this PhD thesis. The approval references were HEC 2018/83 (Study 1, 2, 3), HEC 2018/127 (Study 4), and HEC 2019/100 (Study 5).

Contents

Chapter 1

Introduction

1. Introduction

Bicycle Motocross (BMX) is a relatively new cycling discipline, which consists of single-lap sprint races. On a purpose-built dirt race course (~400 meter), eight riders face several jumps, rollers and banked turns requiring multiple physical and technical actions to be enacted. Each race lasts 30-40 s and riders generally have a 15-30 minute recovery between races, dependent upon the level of competition, with up to six races per day (Cowell et al., 2011). Since first being included in the 2008 Beijing Olympic Games, the sport of BMX has increased its global popularity and consequently researchers have shown more interest in studying this relatively new sport.

Compared to other cycling disciplines, such as road cycling and mountain biking, the relative volume of scientific research on BMX is minimal. While there is available data on the physiological and psychological demands, as well as nutritional interventions for different cycling disciplines (Anderson et al., 2018b; Bejder et al., 2019; Foad et al., 2008; Impellizzeri et al., 2007; Macdermid et al., 2012; Menaspà et al., 2015; Mujika et al., 2001; Olmedilla et al., 2018; Padilla et al., 2000; Spindler et al., 2018, 2019; Whitehead et al., 2016), the unique characteristics (track shape, race period, bike size and features) of BMX cycling may limit the transferability of this data. Therefore, BMX riders and coaches currently have scarce access to appropriate scientific evidence. In particular, there is a lack of scientific research regarding the nature of work demands during BMX racing with specific reference to the accurate physical and physiological requirements of the sport. The ability of sport scientists and coaches to develop and prescribe evidence based training strategies is therefore compromised.

To date, only a small number of studies have investigated the fitness requirements of BMX racing. Laboratory and track based testing procedures have been used in unidimensional studies to assess BMX performance, but in isolation these have failed to account for much of the variation in race performance (Rylands et al., 2019). While partially quantifying the demands of BMX, the measurements made in these studies do not comprehensively characterise the riders' attributes contributing to success. How laboratory physical and physiological variables relate to track performance; how power output changes over the course of a race; how the physiological requirements change over successive races; and how interventions such as the impact of cognitive training or pre-race supplementation will affect riders' performance have yet to receive adequate research attention. In a recent scoping review, Rylands et al. (2019) highlighted the lack of scientific research in the field of BMX cycling and concluded that a multidimensional approach is required to better analyse BMX performance. A multidimensional approach will lead to a greater understanding of factors influencing riders' success and the efficacy of applying different training methods to enhance riders' performance.

One study measured the physiological demands of elite BMX cyclists during a simulated BMX race day (Louis et al., 2013) and demonstrated a high relative $\dot{V}O_2$ (~94 % of $\dot{V}O_{2max}$) during each of the six races. However, the level of this contribution on overall race time was not stated. Furthermore, pre-race lactate levels were not reported and it is therefore not clear, if the accumulated lactate was from prior races or if it was affected by the recovery periods/interventions between races (Louis et al., 2013). Thus, the contribution of the aerobic and anaerobic energy system on race time remains unclear.

Bertucci et al. (2011) showed that elite riders' performance is positively correlated with their jump, standing sprint and Wingate test, and concluded that power output of the lower limb is a factor explaining somewhere between 41-66% of BMX race performance. In this study, riders' power was measured only on the initial straight line section of the track (75 m), thus the power output over the full track length remains unclear. In addition, there was no assessment of the physiological components including heart rate, blood lactate and metabolic pathways involved in the race, in the study by Bertucci et al. (2011). Using multidimensional laboratory tests, including muscular power and strength would provide more valid data in order to highlight BMX performance predicting factors.

BMX race analysis has shown that only 44% of a lap is spent pedalling and throughout the race, multiple muscle groups are involved (Cowell et al., 2011). In a track-based study, Rylands et al. (2017a) highlighted the importance of technical skills in a BMX race by measuring riders' performance under two different conditions. Firstly using the upper body with pumping technique, and then comparing this to employing a non-pumping technique. These researchers demonstrated that the upper body muscle activation in the pumping technique could significantly influence the velocity production. The mean velocity in the pumping trial was 22% greater than the non-pumping trial. Surface (electromyography) EMG was also used to confirm that the appropriate technique was performed in the right trial; however, they reported no significant differences in muscle activation patterns between any of the muscle groups. Therefore, the strength role of different muscle groups on race performance remains unclear.

In addition to recognising the importance of physical training, many athletes and sport coaches believe that using cognitive strategies prior to or during skill execution enhances sport performance (Slimani et al., 2016). One method used extensively to improve general motor tasks is Motor Imagery (MI). MI is a form of simulation where the entire physical experience of an action (e.g. feeling, hearing, and seeing) occurs in the mind and has been shown to improve actual performance (Kosslyn et al., 2001). MI is similar to the real sensory experience, and shares comparable mechanisms used in the actual movement preparation and even stimulates the same brain areas helping to facilitate performance (Kosslyn et al., 2001; Weinberg et al., 2014). Yue et al. (1992) were the first to provide evidence that MI training could improve muscular strength by 22% and suggested that the central programming of voluntary contractions may have led to this improvement.

MI has been shown to have positive effects on absolute and explosive force production, with peak ground reaction forces of an isometric pull being significantly greater when using imagery compared to no imagery (Avila et al., 2015). MI has also been reported to improve pain management and endurance performance in cycling tasks by decreasing the perception of effort (Razon et al., 2014). In world-class endurance cyclists, MI appeared to be a useful method of facilitating positive emotional states (Spindler et al., 2019). While using a mental skills package, including MI, effectively enhanced Triathlon race performance (Thelwell et al., 2003). Considering the similar effects on the brain of MI training compared to actual physical performance, it is therefore argued that MI training could supplement physical practice and help athletes as a mental and physical preparatory tool (Cumming et al., 2012). Despite the positive effects of MI training on muscular strength, power, recovery from fatigue and skill improvement shown in recent research (Lebon et al., 2010; Saumur et al., 2018; Slimani et al., 2016), the usefulness of MI practice on BMX performance remains unknown.

In sports such as BMX, specific MI involves multiple muscle groups, open chain movement patterns and motor skills. BMX coaches seeking performance enhancement through MI intervention, for muscular power and motor skill learning, need research to establish the effects of MI practice on more complex cycling-related tasks. To date, the only published use of MI with BMX riders, had riders simulate their race line positioning using MI method (Di Rienzo et al., 2018). In this study, total power output was found to be higher on the cycle ergometer after focusing on the environmental/emotional context from the external lane using a MI protocol. Given the previously highlighted findings showing the potential for MI to improve strength and power tasks, it seems plausible that MI could make a positive contribution to actual BMX race performance.

Another factor overlooked in BMX specific scientific literature is the role of pre-workout supplementation on race performance. One of the most widespread and socially acceptable stimulants consumed globally, including by sportspeople, is caffeine. The positive ergogenic benefits of caffeine on aerobic performance has been widely accepted. Previous research has also demonstrated that anaerobic performance can improve following caffeine supplementation (Stojanović et al., 2019). Proposed mechanisms include increasing neurotransmitter release and motor unit firing rates (Kalmar, 2005), enhancing muscle contractility as a result of altered calcium kinetics and/or sensitivity (Allen et al., 1995), and decreasing perception of effort related to adenosine receptor antagonism (Davis et al., 2003). A recent meta-analysis demonstrated caffeine might induce meaningful improvements in power and upper body muscular strength (Grgic et al., 2018). Acute improvement in vertical jump height following a single caffeine ingestion has reported roughly equivalent to 4 weeks of plyometric training (Grgic et al., 2018; Markovic, 2007), however other studies have reported no improvements in anaerobic performance following caffeine consumption (Anderson et al., 2018a; Polito et al., 2016). With many methodological considerations including dose, consumption method (capsules/pills, drink, chewing gum) and testing procedures (Goods et al., 2017), the effects of caffeine on short-duration high-intensity performance are equivocal.

Chewing gum is an alternate form of caffeine administration and was first used by the military to rapidly restore alertness and performance (Wickham et al., 2018). Effective absorption of caffeine via gum administration occurs primarily through buccal mucosa within 5-10 min. While this is faster than the 20-30 min taken with capsule ingestion, the total caffeine absorption over time is not different between the two ingestion methods (Syed et al., 2005; Wickham et al., 2018). Previous studies have used caffeine doses ranging from 100-300 mg, administered 5-10 min pre-exercise. Venier et al. (2019) reported up to a 4.5% improvement in vertical jump and power in resistance-trained men after consuming 300 mg caffeinated chewing gum (CAF). Paton et al. (2010) administered 240 mg of CAF via chewing gum to competitive cyclists who completed four sets of five 30 s maximal sprints with 30 s of active recovery between each set. Their results showed that the rate of fatigue in sets 3 and 4 was significantly reduced after CAF versus placebo. Similarly, Ryan et al. (2013) observed enhanced cycling time trial performance after delivering 300 mg of caffeine via chewing gum 5 min before exercise. Interestingly, the same dosage 60 and 120 min pre-exercise failed to show any ergogenic effects. Therefore chewing CAF may prove beneficial where athletes are required to provide a quick increase in repeated anaerobic performance, such as in Bicycle Motocross (BMX) racing. If caffeine enhances short-duration, high-intensity performance by increasing anaerobic power and sprint speed, then BMX riders may benefit from the consumption of CAF. To date, no previous study has investigated the benefits of caffeine administration on BMX performance.

Overall, in order to provide sufficient background knowledge and valid scientific guidelines for BMX coaches and riders, it is important to first highlight different aspects of this sport. When the physical / physiological demands of BMX racing are highlighted, using other aspects of sport science including nutritional supplementation and cognitive training could be used to improve riders' performance. Therefore, a multidisciplinary approach will lead to a greater understanding of factors influencing riders' success and the efficacy of applying different methods to enhance riders' performance.

1.1 Statement of the Problem

Applying a multidisciplinary approach to BMX performance analysis should provide a variety of new scientific data for coaches/riders and add to the currently available yet limited literature on this cycling discipline. More specifically, having a better understanding of the physical demands and key performance indicators will allow for the implementation of targeted training methods for BMX riders. Analysis of race performance can be used to develop or modify the prescription of training specificity, ensuring loads match or exceed expected race demands. Furthermore, identifying the physiological demands of performing successive laps would assist coaches in choosing the most suitable training methods to meet race demands. Considering MI practice as a form of deliberate training, alongside routine field based physical practice, may assist riders enhance their performance. Additionally, gaining a better understanding of pre-race supplementation effects may help coaches and riders determine whether this is beneficial for BMX racing.

1.2 Aims

- To describe the physical and physiological characteristics of BMX riders measured in the laboratory and correlate these measurements with simulated race time to identify key performance indicators.
- To quantify and analyse riders' simulated in-race power production.
- To measure physiological variables over a simulated BMX race day.
- To investigate the effects of 4 weeks MI training on riders' race performance.
- To identify the acute effects of caffeinated chewing gum on race performance.

1.3 Significance of the Study

Using a multidisciplinary approach, this research will provide novel and new findings, which are directly applicable to sub-elite BMX riders. Outcomes from this thesis should help coaches plan targeted training programmes and provide conditioning coaches with a more evidential basis to choose fitness tests to thereby better track performance development. For the first time in BMX research, an applied cognitive strategy in the form of MI training alongside physical practice will be used to provide promising insights into the benefit of MI on BMX cycling performance. Finally, this research should help those BMX riders considering using caffeine as a pre-race supplement to quantify the effectiveness of the ergogenic effects of CAF for BMX racing.

1.4 Organisation and Structure of the Thesis

This thesis is organised as a series of Chapters, based on the manuscripts published in peer-reviewed scientific journals. Following the current Chapter (Introduction), the Review of Literature (Chapter 2) provides the background on BMX cycling, discusses the existing research on the physical attributes and physiological time trial demands of riders, makes a case for the role of MI in sport and cycling performance, and summarises the effects of caffeine consumption on sport performance and cycling tasks in particular. Chapters 3 to 7 include 5 original investigations that address:

- Prediction of track performance in competitive BMX riders from laboratory tests
- Highlighting the determinant physiological factors of simulated BMX time trial
- Analysing the power output during field-based bicycle motor cross (BMX)
- The effects of 4 weeks motor imagery training on simulated BMX time trial performance
- Using caffeinated chewing gum to improve simulated BMX time trial performance

Finally, the Discussion and Conclusion sections (Chapter 8 and 9) integrate the findings of this thesis and present conclusions, implications and directions for future investigation in BMX cycling. Supplementary information including questionnaires, ethical approval, and consent forms related to the data collection are included in the Appendices. The authors' other original research publications over the time-course of the PhD are also presented in the Appendices.

Chapter 2

Literature Review

2 Review of Literature in BMX Cycling

2.1 Foreword

This chapter provides a review of literature that underpins the multidisciplinary programme of research undertaken in the current thesis and focuses mainly on the existing state of research within the area of BMX cycling. Due to limited studies in this field, a wider search was done incorporating other cycling disciplines to provide greater depth of comparison within the literature. In BMX, given that only a few studies have investigated anthropometrical features and physical demands of BMX races, the emphasis of the literature review was more focused on biomechanical studies, which in turn were mainly concentrated on power production, gear selection and technical variation. Only one study investigated the physiological demands of BMX racing, however further research is required using a wider range of riders' competitive levels and considering a wider analysis of performance characteristics. Few researchers have measured power production in the laboratory condition or flat surface set up and limited data is available regarding the power profile of a BMX race, use of mobile power meters and appropriate analyse of their output. Despite the extensive use of cognitive strategies in sport and cycling, there is no data available regarding the use of imagery practices in the area of BMX cycling. In addition, athletes currently use caffeine and other supplement in the hope of enhancing their performance, however, there is no data regarding the effectiveness of caffeine consumption in BMX. Coaches and riders remain uncertain as to the benefits of caffeine consumption prior to racing and further research is required.

2.2 Bicycle Motocross History

Bicycle Motocross (BMX) started in 1968 on the West Coast of the United States and was inspired by the Motorbike (MX). At first, teenagers started the sport by racing their bicycles with motocross gear on self-built tracks (Philippe Campillo, 2007). During the early 1970s, a sanctioning body for BMX was founded and this was considered the official start of BMX racing (Figure 2.1). As the decade progressed, the sport was introduced to other continents. In April 1981, the International Federation of BMX was created and the first World Championship took place in 1982 (Dayton – Ohio; United States). BMX developed rapidly as an individual sport and after several years, its competitive regulations had more points in common with cross-country motor biking. Since January 1993, BMX has been fully integrated into the International Cycling Union (Philippe Campillo, 2007). BMX was introduced to the world as an Olympic level sport for the first time at the 2008 Olympic Games in Beijing, China with individual men’s and women’s events. With further successful editions during the 2012 and 2016 Olympic Games in London and Rio de Janeiro, BMX has established a solid position within cycling sports and as an Olympic cycling discipline.

Figure 2.1 1970’s motocross races, California, from: https://bmx-pros.weebly.com/history.html

Clubs began to spring up in New Zealand and major BMX events started in 1980 and by the end of 1981, there were 70 BMX tracks throughout the country. The first New Zealand BMX national championships were held in Wainuiomata, in Lower Hutt in 1981 (Figure 2.2), and world championships were first held the following year.

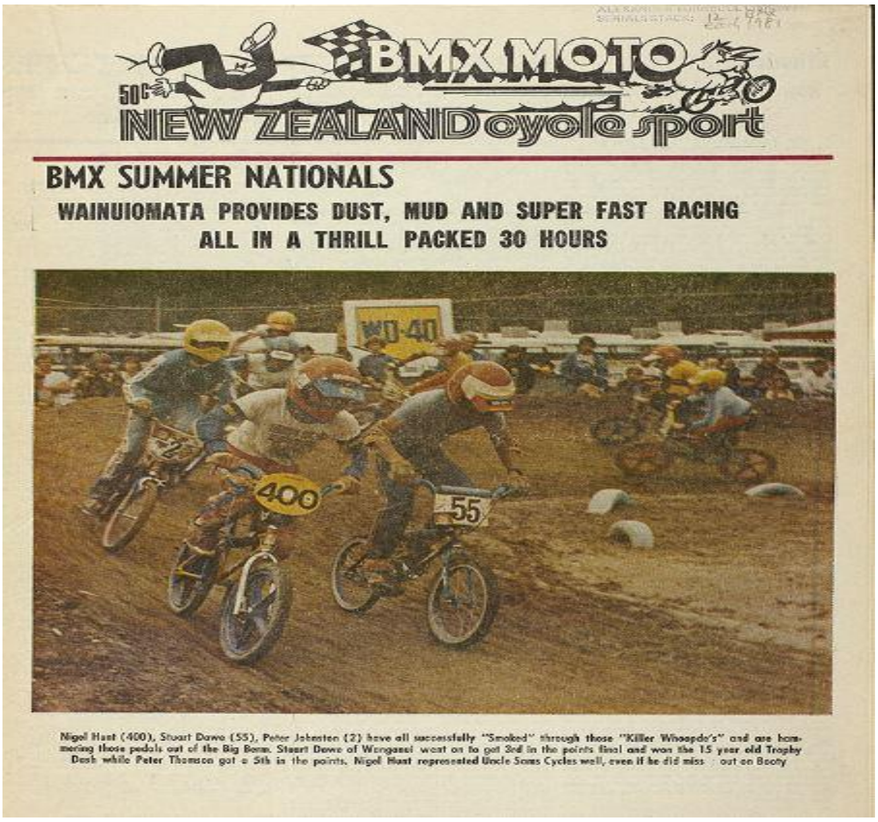

Figure 2.2 o one of the first national events held around 1981 in Wainuiomata, near Wellington, New Zealand. From: BMX Moto: New Zealand Cycle Sport, around 1981 (S-L-539-COVER).

In 2008 competition, New Zealand's top ranked male, Marc Willers, crashed out in the semi-finals, while Sarah Walker came fourth in the women's final. Walker went on to win the BMX World Championship in the Elite and Cruiser classes in 2009 and won a silver medal at the 2012 London Olympics (Simon Kennett, 2015). BMX popularity has been increasing in New Zealand and as at 31st Dec 2018, there were 2092 licensed riders (1654 male & 437 female) spread across 35 affiliated clubs (*BMX New Zealand 2019-AGM-Annual-Report*, 2019).

2.3 Union Cyclist International (UCI) BMX Racing

2.3.1 Classification of Riders

UCI cycling regulations provide a clear guide regarding BMX general rules ("Part VI: BMX Rule Book," 2019). Riders registered to compete in a BMX event are classified according to their age, gender, bicycle style, and competition level. For certain categories, different competition specialties may also be defined as specified within these regulations. For participation in BMX events registered with the UCI international BMX calendar, riders' categories are determined by their age, as defined by the difference between the year of the event and the year of their birth. A rider must be at least 5 years of age to compete in a UCI sanctioned BMX event.

2.3.2 BMX Race Competition Format

During all phases of a BMX race, heats consisting of eight or less riders form the basic unit of competition. A BMX race is composed of three phases including 1) the Motos, 2) the qualifiers, and 3) the final. For all categories, the Motos are subdivided into three rounds. At the end of these three rounds, the riders for each category with the best overall results transfer to the qualifiers or to the final, depending upon the number of confirmed riders entered in that category. For all categories where eight or less riders are registered and confirmed, the aggregate score at the end of the three rounds in the Motos determines the final result and in this case, no final is held. The qualifiers are the elimination phase of a BMX race. They are held for categories with seventeen or more confirmed riders and subdivided into several rounds, which are distinguished from each other by their degree of removal from the final, including 1/32, 1/16, 1/8, 1/4 (quarter finals) and 1/2 (semi-finals), depending on the number of participants. Within each qualifier round, riders in the heats that comprise each category shall race only once. Following each round of the qualifiers, the top four riders from each heat, transfer to the next round of the qualifiers, and are seeded into heats for that round. The top four riders from each semi-final transfer to the final. The final of a BMX competition consists of a single race with nine or more confirmed riders as determined by their finishing positions through the heats.

2.3.3 BMX Track

The BMX start ramp has 5-8 m elevation above grade of the first straight, with an 18º gradient for ~ first 3 meters, and 28º for the rest of the ramp. A typical BMX track ranges between 200-400 m in length and incorporates a variety of jumps, berms (corners), and flat sections. In accordance with the UCI BMX track guide ("Part VI: BMX Rule Book," 2019), the BMX racing venue includes eight main areas (Figure 2.3):

1. The First Straight

2. The First Corner

3. The Second Straight

4. The Second Corner

5. The Third Straight

6. The Third Corner

7. The Fourth Straight

8. The Finish Area

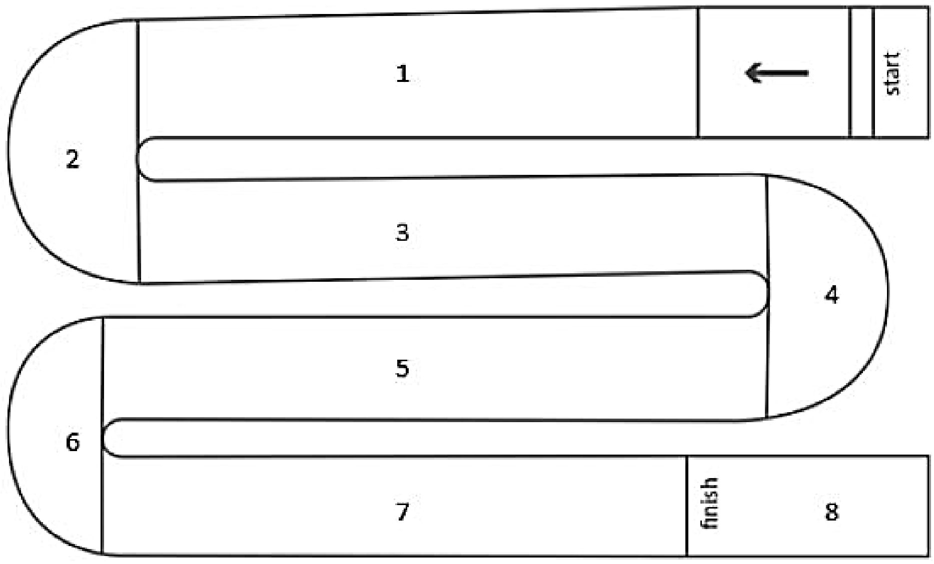

Figure 2.3 BMX track design

2.4 BMX Bike

There are different types of BMX bike adapted for specific uses (Figure 2.4). The racing bike has a 20-inch standard wheel size with a lighter frame than other BMX bikes. This bike is made from aluminium or carbon fibre, as it is designed for speed rather than strength. The racing bike has narrower wheel rims and a slightly longer wheelbase than other BMX bikes. Racing bikes only have rear brakes, which provide the stopping power needed at high speed.

Unlike other cycling bikes (Road, Mountain bike or Cyclo-cross) the BMX bike is not equipped with a gear shifter system. It is not prevented by the UCI rules, simply, riders elect to use a single speed system (Rylands et al., 2017b). Two main reasons for that were, (1) increased risk of the chain falling off the chain ring and (2) insufficient opportunity to change gears during a race (Rylands et al., 2017b). Therefore selecting an optimum gear ratio prior to a race is critical to produce peak power and reduce time to peak power.

In order to select an optimum gear ratio, riders need to consider some important factors. Increasing the gear ratio could increase time to peak power and have a negative effect on start performance. A manipulation of gear ratio could decrease the power output of a rider at a given cadence. The standard gear ratio for a BMX bike is 43-tooth front chain ring and a 16-tooth rear chain ring, more commonly referred to as a 43/16, and many riders use this ratio on their bike (Rylands et al., 2013). To highlight the optimal gear ratio in BMX cycling, Rylands et al. (2017b) used different ratios of 41/16, 43/16 or 45/16 where riders performed three sets of 10 s sprints. Their results showed that riders reached lower peak power and an increased time to peak power comparing the 41/16 to the 43/16. Whilst the larger 45/16 gear ratio enabled riders to produce a higher peak power in a similar time to the trials using a 43/16 gear ratio. Gear selection is therefore a crucial consideration when racing, due to its significant impact on performance.

Figure 2.4 BMX bike types. From: https://www.sporty.co.nz/gisbornebmx/Our-Club-FAQs/Bikes-types-sizing

2.5 Physical and Physiological Demands of BMX

The origins of BMX racing date back as early as the 1960's and academic BMX research began in the 1980s. These research mainly focussed on injury mechanisms and prevention (Brøgger-Jensen et al., 1990; Illingworth, 1985). After inclusion in the 2008 Olympic Games in Beijing, China performance related investigations of BMX increased among academic researchers. Most early research in BMX was focused on biomechanics, kinesiology and physiology. Zabala et al. (2008), was first in the literature reporting physiological characteristics of BMX riders, including power, blood lactate, and rate of perceived exertion (RPE) measurements. In a laboratory based study, the effects of 0.3 $g \cdot kg^{-1}$ Sodium Bicarbonate ingestion in Spanish elite BMX riders was reported to have no ergogenic effects on performance.

Mateo et al. (2011) provided the first insight regarding field-based power data, riding technique and racing on tracks with different difficulty levels. They hypothesized that the track characteristics affect the technical and conditional requirements of the race. Riders' maximal power was measured in an 8-second sprint separately (1343 ± 68 W). The authors reported that peak power in a BMX race is about 85% of maximum power and is achieved within the first 2 s of the race. Using the results of such studies, Cowell et al. (2012b) provided guidelines and conditioning considerations for BMX riders, suggesting that elements such as strength, power, and technical demands need to be considered when selecting conditioning exercises. Specifically, attention should be paid to hip flexion and extension and to the shoulder horizontal adduction/ abduction (Cowell et al., 2012a). They also recommended that for a powerful start, exercises such as the power snatch from a hanging position is useful, as successful performance of this lift requires strength, power and a high rate of force development (RFD). When observing BMX riders' upper-body pulling movement patterns, barbell pulley and dumbbell row with horizontal adducted and abducted shoulders emerge as sport specific exercise.

Research has continued to investigate BMX performance and Bertucci et al. (2011) were the first to measure the power characteristics of elite riders in both laboratory and field conditions. In their study, riders performed a series of jumps and sprints (8 s sprint and 30 s Wingate) in the laboratory, as well as three sprints on the initial straight-line section of a BMX track (75 m). In reporting a track peak power of 1968 ± 210 W, their results revealed that the capacity to produce maximal power was correlated with riders' competitive level. They also highlighted that the results of the counter movement jump, 6 s seated sprint, and 30 s Wingate test are three factors that could help explain riders' performance during the initial straightway of the BMX track. In addition, comparing the results from laboratory and field conditions, power achieved on a standing sprint in the field was 32% higher than that recorded in the laboratory. The authors explained that the large increases in force and peak power were because of natural medial and lateral oscillations of the bike during field-testing.

Novak et al. (2014) quantified several physiological characteristics in different cycling disciplines including BMX, road, cross-country and downhill mountain bike cyclists. Laboratory $\dot{V}O_{2max}$ and peak power in 24 high-performance male cyclists were measured. Their data showed a significant difference in physiological and power output measures across cycling disciplines, with road and cross-country mountain bike cyclists achieving higher $\dot{V}O_{2max}$ and maximum peak power across maximal efforts lasting 15-600 s, than downhill and BMX cyclists. The authors mentioned that, having low values of aerobic capacity amongst BMX cyclists reflects the low priority of aerobic development in this sport. It has been suggested that track-based sprint cycling lasting between 1-4 min may require between 50-84% contribution from aerobic energy production. On the other hand, aerobic capacity may influence repeated sprint performance by allowing an increase in aerobic PCr resynthesis (Tomlin et al., 2001). Therefore, having a higher aerobic capacity should improve BMX riders' recovery between races and improve subsequent race performances, but further data is required to support this statement. Novak et al. (2014) concluded that both downhill and BMX cyclists are more reliant on strength, PCr metabolism and technical ability for success.

Despite the uncertainty regarding the validity of laboratory vs. field data, due to weather conditions and off-season periods, BMX riders often have to practice indoor using stationary bikes or other exercise equipment. Therefore, it is critical for BMX riders to have a better understanding of potential differences between performances in the laboratory compared to the field. Rylands et al. (2015) provided further insights in this area and aimed to ascertain any variation in BMX performance including peak power, torque, and time of power production between the two environments. Eight British elite riders performed three repeated sprints on a cycle ergometer in the laboratory and three 10-second sprints on the BMX track from a 5-meter high start ramp. They reported that peak power was 34% higher on the field (1671 ± 188 W) compared with in the laboratory (1191 ± 188 W). These authors concluded that the application of BMX riders' data used interchangeably between the laboratory and the field should be viewed with caution.

To investigate the metabolic pathways involved in BMX racing, Louis et al. (2013) measured 10 elite BMX cyclists' performance in a simulated race, consisting of 6 laps. After performing an incremental cycling test to measure $\dot{V}O_{2max}$, the cyclists simulated race performance over six laps separated by 30 min recovery. Post-race $\dot{V}O_2$, blood lactate, heart rate, and base excess (an index to quantify the (non-respiratory) metabolic component of acid-base balance) were also monitored. Their result highlighted that elite BMX riders demonstrated a high contribution of both aerobic (94 % of $\dot{V}O_{2max}$) and anaerobic glycolysis reaching 14.5 $mmol \cdot L^{-1}$ of mean blood lactate. However, as the lactate values prior to each lap were not reported, the degree to which lactate accumulated from the previous race remains unclear.

In addition, Louis et al. (2013) results showed that the repetition of six maximal efforts over the simulated race day lead to a significant impairment of the acid-base balance from the third to the final lap, without any significant effect on performance. A BMX race lasts > 45 s and is considered sprint cycling, given the high intensity performance. The relatively high amount of aerobic contribution at the end of the race suggests that the initial high metabolic demands have been carried over. This was potentially due to the energy requirement for technical parts of the race and isometric contraction of the upper body. Despite the unique data presented by Louis et al. (2013), they did not measure the power production during each race and therefore the influence of the aerobic energy system on power production remained unclear.

2.6 BMX Race Analysis

Beside the importance of the physiological demands of BMX racing, analysis of the movements involved in a race is also critical. By characterizing the power output profile and describing the movement pattern in a race, coaches can design optimum training programmes in order to meet the racing demands. Cowell et al. (2012a) performed motion analysis on elite riders' during the 2010 BMX World Championships in South Africa. In their study, riders' movement patterns, pedalling time, jumping and pumping were determined in each time trial. Their results showed that mean race time for elite male BMX riders was 39.67 ± 0.81 s with 30 ± 3 pedal strokes performed. Riders spent 11 s pedalling and 27 s jumping and pumping/coasting in a time trial. Elite women on the other hand, completed the race in an average time of 40.95 ± 0.91 s with 33 ± 5 pedal strokes, and spent 14 s pedalling, with 24 s on technical movements including jumping and pumping. These data showed that the non-pedalling period (jumping and pumping) in a BMX race is significant and further research is required to investigate the role of these technical movements on overall race performance.

Cowell et al. (2012a) also quantified three dominant movement patterns including hip flexion/extension (~ 30 time per lap), knee flexion/extension (~ 30 time per lap), and shoulder horizontal abduction/adduction (~ 20 time per lap) during pedalling and overtaking obstacles. For the first time, they provided an insight regarding different track sections in a time trial. After leaving the start ramp, riders pedalled for ~10 m before taking off the first jump. The entire distance of the first straightway was reported to be ~80 m with three jumps and when including the start ramp, riders spent more time in the first straightway than in any other track section. After the start ramp, which is considered the most critical section of a BMX race, the second most important section of a BMX track is the time to reach the end of the first corner, which is called time cornering. Male riders took ~14 s to reach this point, while female riders reached the end of the first corner after ~18 s (Cowell et al., 2011). Although BMX riders and coaches believe that time cornering can determine the result of a race, its correlation with final race time and other physiological factors is yet to be investigated. The second straightway consists of four jumps where riders jump in quick succession and have little time for pedalling. The third straightway is the most technical part of the track and is called the rhythm section. It was found that this section of track is the most physically demanding of the four sections due to the constant effort the riders need to exert. The riders work for ~8 s, the longest continuous and concentrated effort of the entire lap. The forth (finishing) straightway is the shortest in distance with an average time of ~5 s spent in this section (Cowell et al., 2011).

When analysing the BMX race, previous research has reported that the start section is the most critical part of the race and can influence race time and the riders final ranking (Grigg et al., 2017; Zabala et al., 2009a). The start contains three distinct phases including phase 1, waiting with the front wheel resting against the start gate, phase 2, standing with feet in the toe clips of the pedals, and phase 3, exerting maximum attention to the fall of the start gate. Rylands et al. (2014) analysed the correlation between the relative position at the start gate of a BMX race in relation to finish line placing. In order to determine the influence of the start on the final positioning, elite riders' positions were analysed at four points around the track where time gates were placed at time intervals rather than distance, in the 2012 World Cup series. They subsequently recorded and analysed data from 175 World Cup BMX races (female n = 52, male n = 123) and 348 riders (female n = 108, male n = 240) from four different countries (Canada, Holland, Norway, and USA). Their results showed that riders with the most effective start had better results, as they rarely lost track position following the initial seconds of the race. They reported a significant positive correlation from time gate 1 (1.07 s) through to the finish line. The correlation between the 1st to 3rd placed riders was significantly stronger at timing gate 2 (8.26 s) than for the 4th-8th position. Those riders who placed 1st , 2nd and 3rd at the first split were more likely to achieve a top 3 ranking at the end of the race. They also highlighted the importance of the first 9-10 s of the BMX race, where having a powerful start would potentially determine the final result of the race. Race finish placing is important even in the preliminary qualifying heats of the competition. While the top four qualifiers progress to the next round (dependent upon the number of riders), the order in which they finish and the lap time can affect subsequent lane selection privileges. Leading the race early enables a rider to pick the most advantageous line into the first jump. Existing research in this area is exploratory only using small sample sizes and a non-regulation gate.

The importance of generating maximum power at the start of a race and maintaining power production has raised the need for scientific research related to muscular power development and the significance of race starts. Debraux et al. (2011b) defined factors determining sprint performance by analysing the torque-velocity and the power-velocity relationship among elite BMX riders in 80 m sprints on flat ground. Their result showed that maximum power, torque, and cadence are significant determining factors of performance. It was also reported that the gear ratio is a factor that can influence power output and displacement velocity.

Further studies analysing power production in BMX have used mobile power meters, which can be fitted to a bicycle to measure power output on the field. Three different types of power meters including; SRM Powermeter (Schoberer Rad Messtechnik, Germany), PowerTap (PowerTap, USA) and G-Cog (Rennen Design Group, USA) have previously been used in BMX studies. The first power meter which was produced specially for BMX was G-Cog and provided data at 250 Hz sampling rate compared with SRM (2 Hz) and PowerTap (0.8 Hz). Bertucci et al. (2013) tested the validity and reliability of the G-Cog power meter and their results failed to show any correlation with those obtained from the SRM. Rylands et al. (2013) used an SRM power meter to assess velocity production in six elite BMX riders and conducted a 50 m maximal sprint test to determine peak power, and a 200 m sprint test to assess riders' fatigue. Their results revealed that BMX riders had lower peak power and comparatively lower power-to-weight ratio than track sprint cyclists. BMX riders also fatigued at a greater rate than the track sprinters and mountain bike riders. The author concluded that BMX riders produced velocity, initially using power and cadence, but reduced their power production and relied on cadence to continue velocity production. This may be a result of using a fixed gear ratio (43 to 16 gear ratio), as the resistive force of the gear is overcome in a short period. Thus, peak velocity and peak power might not represent maximal power and maximal velocity riders are physically able to perform. Increasing the gear ratio may affect the peak power production and therefore increase the peak velocity. Rylands et al. (2013) highlighted that the increased gear ratio may also have a positive effect on the fatigue index of riders if peak and minimal power outputs increase. Therefore, increasing the resistive force by increasing the gear ratio may aid riders in maintaining a higher velocity and reducing the fatigue index.

The influence of power and pedal rates in cycling is well presented in a number of other cycling disciplines. For example, Dorel et al. (2005) showed the importance of the power and cadence relationship in 12 elite sprint cyclists. They concluded that the optimisation of the ratio between peak power and optimal cadence is a key factor in track cycling performance. This resulted in a peak power of 1600 W for a cadence of 129.8 ± 4.7 rev·min^{-1}. Abbiss et al. (2009) found that the peak performance outcome of endurance cycling events of > 4 h was recorded at an optimal ratio of 100-120 rev·min^{-1}. These authors highlighted that the relationship between cadence and power is specific to each individual cycling discipline. Rylands et al. (2017b) in a laboratory based study, investigated the relationship between optimal power production and cadence in 17 elite BMX riders using a broad range of cadences including 90, 100, 120, and 140 rev·min^{-1}. Their results presented that peak power achieved at a cadence of 100 rev·min^{-1}.

Despite the effect of cadence on power production being presented for the first time, the impact of track and environmental conditions on power output is yet to be investigated.

2.7 Cognitive Training in BMX Cycling

2.7.1 Motor Imagery

Many athletes believe that optimal performance is contingent upon cognitive strategies just as much as it is on physical and technical preparation (Tod et al., 2003). Nevertheless, sport psychologist’s reports show that athletes need to undertake one or more cognitive strategies prior to or during performance in training and competition (McCormick et al., 2015; Tod et al., 2015) to achieve success. Using strategies such as imagery, self-talk and goal setting is designed to increase focus attention, physical and mental activation, and build self-efficacy (Tod et al., 2015). One of the most popular cognitive strategies among athletes is imagery.

Motor imagery (MI) is the mental simulation of an action without any corresponding motor output (Jeannerod, 1994). Research has shown many similarities between executed and imagined movement at both a behavioural and neurophysiological level. At the behavioural level, a temporal congruence between the production of a movement and its mental simulation has been observed (Papaxanthis et al., 2012). Regarding the neurophysiological level, many studies have established a common neural support between mental and actual conditions. Particularly, similar activation has been found in the premotor cortex, the supplementary area, the inferior and superior parietal lobule, the cerebellum, the basal ganglia and the prefrontal cortex (Hétu et al., 2013). This functional relationship provides a direct approach for researchers to study the importance of covert motor processes in everyday life (Reiser et al., 2011). Because of this wide application and ability to gain insight into underlying mechanisms, imagery is of interest to a range of fields including cognitive psychology, neuropsychology, neurophysiology, neurorehabilitation, motor learning, motor control, and physiotherapy (Cumming et al., 2012). This technique is a well-known performance enhancing strategy and is used extensively in different sports.

MI is also defined as using all the senses to recreate or create an experience in the mind (Cumming et al., 2014). This technique is a well-known performance enhancing strategy and is used extensively in applied fields such as sport, dance, and exercise psychology (Cumming et al., 2014; Slimani et al., 2016). MI is meant to aid self-regulation of feelings, thoughts, and behaviours, and it is a characteristic of successful performers. Both cognitive and primary motor tasks benefit significantly from MI (Feltz et al., 1983). Recent research has shown that MI improves motor tasks including muscular strength/power (Slimani et al., 2016), sprinting (Hammoudi-Nassib et al., 2014) and endurance (McCormick et al., 2015). The technique improvement related to MI is explained by several mechanisms (Martin et al., 1995; Slimani et al., 2016; Vadoa et al., 1997) such as self-efficacy, motivation, self-confidence and managing competitive anxiety.

There are different forms of MI including the auditory, olfactory, tactile, kinaesthetic, and visual modes (Cumming et al., 2014). In addition, MI can be performed using basic perspectives such as an internal or external perspective. The internal perspective mainly involves imagining from within the body and experiencing the motor act without overt movement. For instance, the subject imagines that he/she is performing the movement and feels the contracting muscle and kinaesthetic sensation. While external imagery involves imagining the action as if it is outside the body, where the motor task is generated in the subject's mind (Tod et al., 2015). The experimental research findings indicated that internal imagery was more beneficial for closed skills than external imagery, whereas performance involving open skills might benefit most from external imagery (Slimani et al., 2016).

MI training has been reported to increase the performance of strength-based tasks such as voluntary muscular contraction for both distal and proximal muscles of the upper and lower limb (Ranganathan et al., 2004; Reiser et al., 2011; Zijdewind et al., 2003). Looking to the literature, the applicability of mental training to the field of strength training was researched by Yue et al. (1992), who demonstrated a significant effect of motor imagery in an isometric force production task following 4 weeks of isometric force production, with either physical maximum voluntary contraction or mental training. Their results showed a comparable strength gain in both groups compared to the control group with no training. In addition, research has suggested that MI training could improve functional recovery after short-term muscular immobilization by the reduction of strength loss. Newsom et al. (2003) found that MI prevention intervention was effective in reducing strength loss of wrist flexion/extension after short-term muscle immobilization. In addition, a report by Clark et al. (2014) showed the effectiveness of integrating mental imagery into the rehabilitation process on the reduction of strength loss and voluntary activation. Therefore, MI may be considered as a therapeutic strategy to help injured patients recover their motor function post knee surgery (Lebon et al., 2012), as MI centrally organizes a motor program and activates neurons within various areas of the brain responsible for priming the execution of the motor tasks. Previous research has demonstrated the presence of electrical muscle activity during subliminal mental simulation of a movement. It was suggested that MI is accompanied by electromyography (EMG) activity and selective muscle activation. The increase in the magnitude of EMG caused by MI could be the result of an increased number of active motor units and their firing frequencies. These findings could engage athletes to include MI as part of their routine training; however, they require a clear framework to follow.

Hall et al. (1998) developed a framework to examine the different motivational and cognitive functions of imagery used by athletes. They indicated that imagery can be used to envisage specific skills (cognitive specific imagery), rehearse strategies (cognitive general imagery), remind oneself of one's goal (motivational specific imagery), and help control arousal (motivational general-arousal imagery). Hall and colleagues found that elite athletes' use of mastery-oriented imagery (for instance, motivational general-mastery and motivational specific imagery) was predictive of performance. Given the importance of pre-competition psychological preparation and the integration of imagery use during that period, Beauchamp et al. (2002) used the taxonomy of sport imagery introduced by Hall et al. (1998). They aimed to examine athletes' use of imagery immediately before competition and the relationship between self-efficacy, pre-competition imagery use and golf performance. Their results showed elevated self-efficacy should be associated with more frequent use of pre-competition imagery.

2.7.2 PETTLEP Model

Several studies highlighted enhancement in sport performance following MI practice. Isaac (1992) showed that six weeks of trampoline training, alongside MI training, improved the skill of actual movement in the MI group compared to the control group (no imagery). Although the effect of MI training alone, does not produce the same results as actual training, it could be used as a beneficial supplementary measure to improve overall athletic performance. Using MI practice as a form of deliberate practice, elite athletes (70-90%) reported an improvement in their sport performance, which was more than amateur athletes (Cumming et al., 2002). Despite the studies supporting the effective notion of MI in sport performance, some researchers have criticized the lack of a theoretical and empirical base for scientific studies and applied work conducted on this topic. In response to this, Holmes et al. (2001) established the PETTLEP model. The model was based on neuroscience research findings regarding the same neurophysiological processes between imagery and actual movement and the notion that this functional equivalent provided a possible explanation for the performance improvement effect of imagery. The PETTLEP relates to several important components namely; Physical, Environment, Task, Timing, Learning, Emotion and Perspective that need to be considered when applying MI interventions (Holmes et al., 2001). Considering the notion of these elements are very important in order to design MI training programmes. In the following paragraphs, definition of each component is presented using Holmes et al. (2001) guideline.

The physical component of this model is related to the subject's responses in a sporting situation. Holmes et al. (2001) argued that imagery is more effective when it includes all of the senses, and kinaesthetic sensations that would be engaged and experienced, during actual performance. For instance, imagery that incites physiological responses such as heart rate, lactic acid accumulation and muscular contraction can be evocative of actual performance for athletes. In addition to this, actions such as holding a hockey stick, wearing a cycling helmet or adopting the sporting posture, would enhance the physical nature of the imagery.

The Environmental part of the model refers to the physical environment in which imagery is performed. The environment when imagining the performance should be as identical as possible to the actual performing condition, in order to access the same motor representation. For instance, a football player should perform imagery while standing on the field. If a similar environment is not possible, a photograph of the venue or audiotapes of the noise of the crowd can be used.

The Task component is where the imagined task needs to be closely matched to the actual task, which is considered a very important component of the model. The task should be specific to the performer, as they focus on the same thoughts, feelings, and actions, as they would have during the physical performance of the task. To achieve the functionally equivalent imagery, it is important that the subject focuses on the actual response, by eliciting and reinforcing verbal reports of physiological and behavioural involvement in the scene, therefore, emphasizing a kinaesthetic orientation toward the imagery.

Timing is a crucial component of actual game situations and in the execution of specific skills in elite sport. Furthermore, if the action were imagined at competition pace, it would make the timing component even more beneficial. Functionally equivalent timing may be only appropriate when the performer masters the skill he or she is imagining. For instance, the duration of mentally simulated actions should be similar with the time taken to execute the same movement.

The Learning component of the model refers to the adaptation of imagery content in relation to the stage of learning. As the participants skill level may vary from competitive to autonomous, the motor representation and associated responses will change and therefore the imagery content must also change to reflect this. For instance, at first, the performer has to think about the movement a great deal and thus the imagery may focus on correct technique with elements such as limb positioning being central. After developing a more advanced skill level, the performer would not have to think about the technique and therefore imagery will focus more on the feel of the movement. For example, elite swimmers often talk about the feel of the water.

In order to achieve optimal functional equivalence, the performer should try to experience all of the Emotion and arousal associated with the performance. It is important that the performer's emotional responses and his/her understanding of the scenario are included in the imagery. For instance, the feeling of excitement that the performer is feeling during performance should be an important part of the imagery. Negative thoughts should be replaced where possible by positive ones. In a sporting situation, this may include adrenaline excitement, nerves, and memories of previous performances. For instance, while a cyclist is imagining the start line of a race, he/she should feel all the emotions and feeling of that particular situation, such as increased heart rate, sweating, hearing the crowd etc.

The final component of the model is Perspective, which refers to the way that imagery is viewed. From a functional equivalence perspective, internal (first person) imagery would appear preferable as it more closely approximates the athlete's view when performing. Recent research using positron emission tomography (PET) supports the idea that internal imagery produces more functionally equivalent brain activity than external imagery. PET in a functional imaging technique that uses radioactive substances, known as radiotracers, to visualise and measure changes in metabolic processes, and in other physiological activities including blood flow, regional chemical composition, and absorption. It may be most beneficial, therefore, for athletes to use a combination of internal and external perspectives. More advanced performers will be able to switch from one perspective to another and, in doing so, gain advantage from both perspectives, and thus optimize the imagery experience.

The PETTLEP model has been used within sport by different studies, and these studies have found that incorporating more elements often leads to greater performance, as well as improvement in confidence and motivation. Smith et al. (2007) reported that combining the physical and environmental elements together was more effective for improving field hockey penalty flicks compared to both a physical element only condition and a traditional imagery condition. PETTLEP imagery, combined with physical practice, is also more effective compared to traditional imagery or physical practice itself (Smith et al., 2008). Traditional imagery involves subjects sitting quietly in a separate room from the performance environment and traditional imagery also involves certain PETTLEP elements that are common to all imagery interventions, such as task, perspective, and emotion. Based on findings comparing PETTLEP imagery to traditional imagery, it is suggested that the physical and environmental elements are key, and they add value over and above the more traditional elements (Wakefield et al., 2013).

In the sporting context, the two main modalities of movement imagery that are used to enhance performance are visual and kinesthetic. Visual imagery involves seeing the movement that can be experienced from two different perspectives. External visual imagery (EVI; third-person perspective) involves watching yourself perform the movement as if from another person's point of view, while internal visual imagery (IVI; first-person perspective) involves viewing the movement with your own eyes as if actually performing the movement (Morris et al., 2005). Kinesthetic imagery (KI) refers to imagining the feelings and sensations associated with the movement. Although EVI, IVI, and KI have been identified as separate constructs (Williams et al., 2012) combining visual and kinesthetic imagery is believed to be most beneficial for improving performance, both directly and indirectly through psychological variables such as confidence. More recently, Anuar et al. (2016) compared the effect of PETTLEP imagery against traditional imagery on the ease and vividness of EVI, IVI, and KI of movement. Their results support the notion that incorporating PETTLEP elements would increase participants' ease and vividness of imagining movements using EVI, IVI, and KI. Anuar et al. (2016) concluded that athletes should be encouraged to apply PETTLEP model during imagery sessions when using IVI and KI imagery.

2.7.3 Imagery Ability

The other important factor that influences the quality and effectiveness of MI training as a performance-enhancing strategy is imagery ability. It is defined as the individual's ability to generate and control vivid images (Martin et al., 1999). Vividness of an image is described as "its clarity and 'sharpness' or sensory richness," and controllability as the "ease and accuracy with which an image can be transformed or manipulated in one's mind" (p. 158). Vividness is an aspect of imagery concerned with the actual generation of the image, whereas controllability refers to the transformation and maintenance of the image once it has been generated (Moran, 1993). It is reported that successful athletes have greater vividness of movement images (Cumming et al., 2012). While some individuals fundamentally find it easier to image than others, characteristics related with imaging can be improved. Consequently, a person's ability to create and control images is partly fixed and partly adjustable, with the former reflected by the developmental changes occurring as a result of maturation (Cumming et al., 2012).

As individual differences in imagery ability are important to consider, it is common practice to screen subjects before the intervention. To accomplish this task, researchers require a valid and reliable measurement method to assess imagery ability. The most common method is to use self-report questionnaires, with the two most popular and well-established being the Vividness of Movement Imagery Questionnaire (VMIQ2) (Roberts et al., 2008) and the revised Movement Imagery Questionnaire (MIQ-R) to measure visual and kinesthetic ability to image simple movements and actions. In addition, Williams et al. (2011) developed an imagery ability assessment known as Sport Imagery Ability Questionnaire (SIAQ). The SIAQ assesses performer's ability to image five different sport-specific imagery types: skill, strategy, goal, affect, and mastery.

Both visual imagery perspectives are proposed to serve distinctive benefits. For example, when performing tasks such as the learning of movement and when form or body coordination is important, the external visual imagery perspective is valuable. In this case, the performer is presented with a view of how the movement or action should be performed. On the other hand, internal visual imagery is thought to be beneficial for open skills when timing is important. Therefore, the performer is able to rehearse spatial location and when a movement should be initiated. It was suggested that individuals may find it easier to see the form-based movements of the MIQ-R from an external visual imagery perspective (Callow et al., 2004). In addition, some individuals prefer to image from one perspective more than another, while others prefer changing between the two (e.g., Cumming & Ste-Marie, 2001) and altering their images to take advantage of different viewing angles (e.g., Callow & Roberts, 2010). Altogether, it appears logical and necessary that the MIQ-R can be extended to fully capture an individual's visual imagery ability. In order to extend MIQ-R to more fully capture the performer's VI ability and to separately assess EVI, IVI, and KI ability, Williams et al. (2012) developed an adaptation of MIQ-R, called the Movement Imagery Questionnaire-3 (MIQ-3). The rating scales of the MIQ-3 vary from 1 (very hard to see/feel) to 7 (very easy to see/feel), with a higher average score for a subscale representing a greater ease of imaging. According to Williams et al. (2012), MIQ-3 demonstrates a good internal reliability for each subscale.

2.7.4 Motor Imagery and Cycling

MI training is shown to be effective for improving several aspects of motor performance. By enhancing muscular strength (Grospretre et al., 2019; Ranganathan et al., 2004; Scott et al., 2018; Yue et al., 1992), preventing loss of muscular force (Clark et al., 2014), and improving movement speed/accuracy (Papaxanthis et al., 2012), MI has been extensively included in various motor task related contents. The positive influence of MI practice on the representation of complex actions have been reported by Frank et al. (2016). A combination of physical and mental practice would lead to better structure and elaborate presentations, compared to physical practice alone (Ruffino et al., 2017). More recently, in a literature review, Pavlik et al. (2016) reported that MI is being extensively used by dancers and teachers during class as teaching tool to emphasize the quality of a specific movement, or to describe the execution of a step. Despite the wide range of MI, limited research has investigated the effects of MI intervention in sprint cycling performance.

Success in elite cycling requires athletes to perform at their psychological peak when placed under severe physiological load (Spindler et al., 2018). MI training has been found to benefit many cognitive elements including emotion, confidence and decision-making. Therefore, Spindler et al. (2019) investigated the effect of motivational general-arousal imagery on decision making performance of elite endurance cyclists under physiological duress. Their findings suggested that while motivational-general arousal imagery might be a useful method to induce positive emotions, it is unlikely to improve cognitive performance. In another cycling related study, MI has been used as an assistive tool to simulate the context of an actual BMX start from the internal and the external lanes (Di Rienzo et al., 2018). In their study, BMX start performance was assessed in both experimental (cycle ergometer with MI) and actual start gate contexts. Their results showed that on the cycle ergometer, the total power output was higher after the contextualization MI routine focusing on the environmental/emotional context from the external lane. Despite the positive effects of MI on cycling performance, to date no data is available on the use of MI as a training tool in the form of deliberate training beside actual physical BMX practice. Further research is required to provide better understanding of this cognitive strategy in BMX literature.

2.8 Caffeine Supplementation in BMX Cycling

2.8.1 Caffeine

Caffeine (1,3,7-trimethylxanthine) is commonly found in over-the-counter medications, coffee, tea, cola, chocolate and various other products. It is metabolized in the liver to dimethyxanthines (paraxanthine, theobromine, theophylline). Metabolites of caffeine have been shown to cause vasodilation and increases urine volume (theobromine), smooth muscle relaxation (theophylline), and stimulation of lipolysis (paraxanthine) (Graham, 2001b).

Caffeine is consumed daily by ~65% of the world's population' for its stimulating effects such as reducing fatigue and increasing wakefulness, and its ability to enhance mental and physical performance (Burke, 2008; Dodd et al., 1993). Athletes also consume caffeine as an ergogenic aid pre training and competition as evidence supports that caffeine consumption will improve athletic performance (Stojanović et al., 2019; Wickham et al., 2018; Woolf et al., 2008).

The International Society of Sports Nutrition (ISSN) defines an ergogenic aid as any nutritional practice that can help improve exercise performance capacity or enhance physical strength (Kreider et al., 2010). Caffeine is a central nervous simulant, and there are three potential cellular mechanisms that could explain caffeine's ergogenic effects on performance. Firstly, caffeine elevates myofilament affinity for CA^{2+} and increases CA^{2+} release from the sarcoplasmic reticulum (SR) of skeletal muscle. Secondly, increasing cellular action caused by accumulation of cyclic-3-5-adenosine monophosphate (cAMP) in skeletal tissue and adipocytes and finally, competitive inhibition of adenosine receptors in the central nervous system and somatic cells (Dodd et al., 1993).

Caffeine was found to increase twitch tension development that supports greater myofilament affinity for CA^{2+} (Gulati et al., 1985). It was also reported that consumption of a large dose of caffeine increased skeletal muscle contraction force and enhanced CA^{2+} release from the SR membrane, or the junction between the T-tubule and terminal cisternae, without effecting the rate of CA^{2+} re-uptake (Kovács et al., 1983). These would lead to a greater binding of CA^{2+} to troponin and increase actin-myosin filament cross-bridging that results in a greater force development by contracting muscle. Caffeine can also reduce the charge needed to reach the muscular contraction threshold; therefore, lowering the electrical threshold for contraction (Brooks et al., 2005; Kovács et al., 1983).

Caffeine increases the cAMP level via increasing blood catecholamine levels, as well as, inhibiting the phosphodiesterase enzyme (Dodd et al., 1993). The most abundant catecholamines in the human body are epinephrine (adrenaline) and norepinephrine (noradrenaline). Epinephrine and norepinephrine are released from the adrenal medulla as a response to the "fight or flight" mechanism when the Sympathetic Nervous System (SNS) is stimulated (Brooks et al., 2005). Catecholamines such as epinephrine can enhance cAMP levels via activating adenylate cycles, that stimulates the formation of cAMP from ATP in the cell (Brooks et al., 2005; Dodd et al., 1993). The cAMP simulates the release of Hormone-sensitive lipase (HSL). Then HSL increases lipolysis and level of free fatty acids (FFA) where FFA increases mitochondrial activity and β-Oxidation (Brooks et al., 2005).

Caffeine's structure is similar to that of adenosine and functions as an adenosine receptor antagonist (Dodd et al., 1993). Thus, caffeine can bind to adenosine receptors in the brain and peripheral tissue. This blocks the binding of adenosine and results in a myriad of interacting responses (Dodd et al., 1993; Graham, 2001a) and could cause behavioural depressions (Holtzman et al., 1991). Therefore, caffeine has a notable effect on the stimulation of the central nervous system. Potential mechanisms of caffeine on the CNS and on hormonal, metabolic, muscular, cardiovascular, pulmonary, and renal functions during rest and exercise are shown in Figures 2.5 and 2.6 reported by Sökmen et al. (2008).

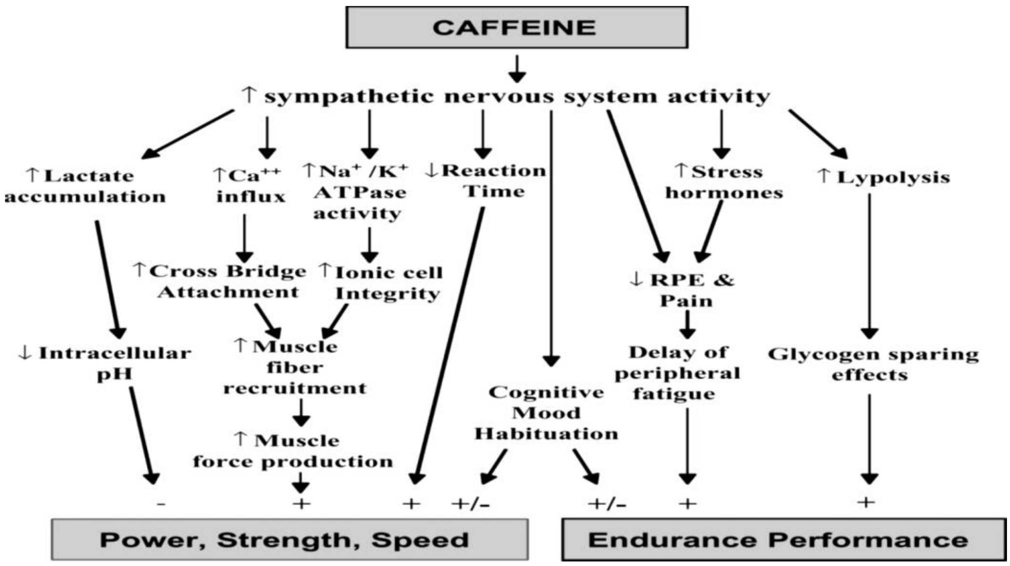

Figure 2.5 Potential mechanisms of caffeine in endurance and power events. Sökmen et al. (2008)

2.8.2 Performance Effects

Historically, the ergogenic properties of caffeine were first reported by Rivers et al. (1907) and before 2004, athletes were disqualified from the Olympic Games if caffeine levels in their urine exceeded 12 μg/mL (McLellan et al., 2016). Caffeine in higher doses may produce several well-known toxic effects (Andrade et al., 2018). Symptoms of caffeine intoxication may include headache, fever, nausea, vomiting, tachycardia, dizziness, tinnitus, anxiety, irritability, insomnia and seizures. Cardiac arrhythmias are considered the most common cause of caffeine-related death (Andrade et al., 2018). Therefore, caffeine consumption was banned by the World Anti-Doping Agency (WADA) for 20 years (1984 - 2004).

Since 2004, when caffeine was removed from the WADA's list of within-competition banned substances, the National Collegiate Athletic Association permits caffeine usage to a certain range. The maximum allowable urinary level is 15 μg/mL (approximately 8 cups of coffee or

800 mg) (Cappelletti et al., 2018) and this is currently a legal method of enhancing performance in training sessions and athletic competitions (Del Coso et al., 2011). For instance, caffeine was contained in almost 75% of the urine samples collected in 2004 to 2008 as a part of doping controls (Del Coso et al., 2011).

Over the last decade, several reviews have examined the efficacy of caffeine as an ergogenic aid (Wickham et al., 2018). The current approach is to use low doses of caffeine which apply ergogenic effects via interactions with the CNS and have slight caffeine-related side effects (Spriet, 2014).

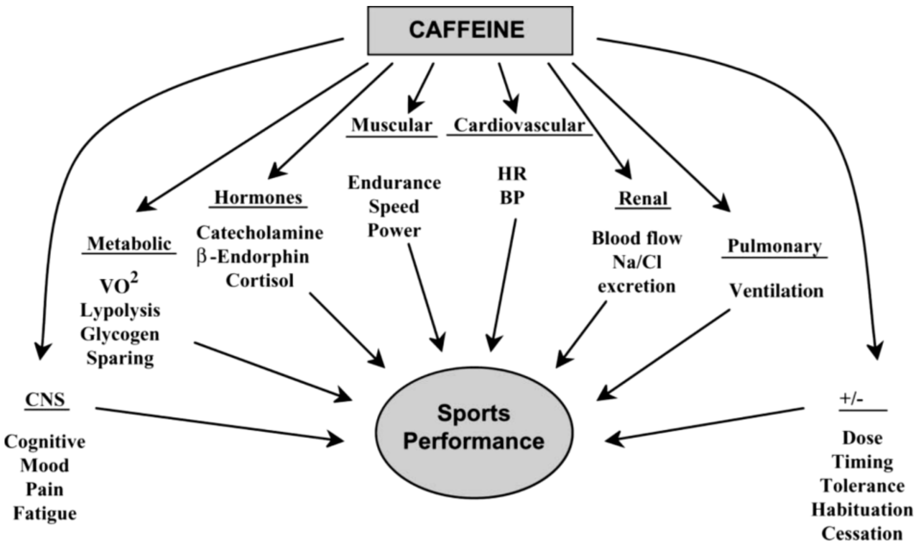

Figure 2.6 The effects of caffeine on body systems and sports performance. Sökmen et al. (2008)

2.8.3 Caffeine and Aerobic Performance

Caffeine is recognized as one of the most commonly used ergogenic aids, especially among endurance athletes (Burke, 2008; Costill et al., 1978; Cox et al., 2002; Glaister et al., 2018; Graham, 2001b). The interest in caffeine's ergogenic benefits began due to the research by Costill et al. (1978) who reported that consuming 330 mg caffeine from coffee, improved cycling time to exhaustion. Trained cyclists in this study could extend their riding time at 80% of VO_{2max} from 75 min in the placebo condition to 90 min following caffeine ingestion. The primary mechanism hypothesized around caffeine's performance effects is the ability to modulate pain, fatigue, and vigour (Costill et al., 1978; Cox et al., 2002; Doherty et al., 2005; Goldstein et al., 2010). This is attributed mainly to the antagonism of adenosine receptors in the brain, which relieves central fatigue symptoms and is often considered as caffeine's primary ergogenic mechanism (Cole et al., 1996; Goldstein et al., 2010). The common outcome measures to evaluate endurance performance included Ratings of Perceived Exertion (RPE), pleasure ratings, fatigue, and exercise trial performance. Previous studies reported a lower in-task RPE among participants who consumed caffeine, compared with placebo or control conditions (Azevedo et al., 2016; Backhouse et al., 2011; Killen et al., 2013).

Caffeine can also affect aerobic performance via peripheral mechanisms including effort consciousness, voluntary motor unit activation, contractile muscle function, release and uptake of calcium at SR, and the activity of sodium/potassium ATPase pumps (Barcelos et al., 2020). In addition, caffeine increases β-endorphin secretion, free fatty acid mobilization, spare glycogen, and circulating epinephrine (Barcelos et al., 2020; Goldstein et al., 2010). A meta-analysis by Doherty et al. (2004) reported large improvements in endurance performance during cycling tests (22 ± 13%) and running tests (19 ± 13%) following caffeine ingestion. In a systematic review by (Ganio et al., 2009) the effects of caffeine on endurance performance from 1985 to 2007 were presented. The authors reported a percentage change in performance following caffeine usage compared to placebo, which gives some estimate of the overall improvement effect of 3.2 ± 4.3% across all exercise modalities. More recently, in another meta-analysis, Southward et al. (2018) critically evaluated the effect of acute caffeine ingestion on endurance time-trial performance. They reported that acute caffeine consumption has a small but significant effect on endurance performance (effect size = 0.24-0.41, $p < 0.001$), evident by an increase in mean power output (~3%) and faster time-trial time (~2.5%) compared with placebo. Southward and colleagues also concluded that it is unlikely that caffeine gives elite endurance athletes an essential edge over their competitiors, due to the prevalence of caffeine use being 89%. However, using caffeine may prevent them from being disadvantaged compared to components who are also likely to use caffeine. For example, the fastest official half-marathon time is 58:23 min, and the average performance improvement found by Southward et al. (2018) was 2.1 %. Over a 58 min event this equates to a 1.22-min improvement. This amount of time equates to the difference between first (58:23) and 97th place (59:45) in the list of the current fastest half-marathon times. Therefore, whether or not an athlete consumes caffeine prior to or during an endurance event, may have a large effect on their overall performance outcomes. It is the job of the sports practitioner to make their athletes aware of the benefits and the risks of using an ergogenic aid such as caffeine.

2.8.4 Caffeine and Anaerobic Performance

Anaerobic effect of exercise happens when the lactate threshold has reached the maximal lactate steady state (MLSS), this is the maximum blood lactate concentration and submaximal workload that can be sustained over time without constant blood lactate accumulation (Billat et al., 2003). One common test of anaerobic capacity and power output is the Wingate test, which consists of a short warm-up and of pedalling or arm cranking at a maximal speed for 30 s. Several studies explored the effects of caffeine intake on Wingate performance, with equivocal findings. For example, (Greer et al., 1998a) showed an ergolytic effect of caffeine consumption on power output of the fourth Wingate bout compared with placebo. However, in a follow-up work by the same author, no significant effect of caffeine was reported (Greer et al., 2006). It is worth noting that 12 out of 18 subjects in that study did experience an increase in peak power following caffeine consumption compared with placebo. In contrast, Woolf et al. (2008)

showed that a moderate dose (5 mg/kg) of caffeine resulted in more total weight lofted for the chest press and a greater peak power attained during the Wingate test in competitive athletes. More recently, Salinero et al. (2017) showed that caffeine ingestion in a group of young men and women, increased both peak power and mean power output during the Wingate test. In a recent meta-analysis study, Grgic (2017) indicated that caffeine ingestion can augment mean and peak power output on the Wingate test by + 3% and + 4%, respectively. This meta-analysis supported the notion that caffeine ingestion can also be ergogenic for anaerobic performance.

The first explanation raised for caffeine's ergogenic effect on anaerobic exercise involves the stimulation of the sympathetic nervous system and, thus, the increased catecholamine release (Souza et al., 2017). This could potentially enhance performances via a stimulated glycolytic pathway, but it seems unlikely that this is the primary mechanism responsible for the caffeine ergogenic effect (Barcelos et al., 2020). Studies have shown that enhanced adrenaline levels and better performance are not always related to higher glycolytic flux (Bell et al., 2001). It is suggested that the greater glycolytic output is not directly affected by caffeine but has an indirect effect. Firstly by CNS stimulation through adenosine receptor antagonism, as previously stated. Considering that adenosine enhances pain perception and reduces natural locomotor activity (Davis et al., 2009), it is likely to suggest that the adenosine inhibitory effect induced by caffeine, leads to modified pain perception and sustained motor unit firing rates and neuroexcitability. This is the leading hypothesis theory for the ergogenic effect of caffeine on enhanced performances, particularly during anaerobic performance. A second explanation presumes that caffeine directly affects the skeletal muscle, including ions transportation channels, particularly sodium and potassium, and by phosphodiesterase enzyme inhibition, leading to increasing cAMP levels. Caffeine also exerts a direct effect on metabolic phosphorylase-like enzymes regulation and calcium mobilization from the SR, consequently increasing the intracellular calcium levels on the myocytes, which facilitate the contract signal stimulation at skeletal muscle (McLellan et al., 2016). In this way, caffeine ingestion may be able to increase both peak power output and mean power output during the Wingate test because it appears to provide significant ergogenic effect on muscle strength and power. It may also lead to a substantial increase in isokinetic performance (Barcelos et al., 2020).

2.8.5 Alternative Form of Caffeine Administration

Ingesting tablets/capsules with water, or drinking coffee, are known as traditional forms of caffeine administration in research and athletic settings. The caffeine is quickly swallowed and the majority is absorbed into the blood from the intestine, with the possibility that a small amount is absorbed in the buccal mucosa (Wickham et al., 2018). Caffeinated sports drinks have also been studied for many years, with most reports demonstrating that caffeine added to a sports drink has a further performance enhancing effect above that of a carbohydrate (CHO)-electrolyte solution alone (Kovacs et al., 1998; Spriet, 2014). In addition, caffeine is currently available in gels, bars, gums, lozenges and energy drinks, which may affect how quickly the caffeine is absorbed into the blood from the buccal mucosa and intestines (Wickham et al., 2018). Recent evidence showed that mouth rinsing with caffeine may activate sensors in the oral cavity with direct connections to the brain, that could ultimately affect athletic performance (Doering et al., 2014). Manufacturers are also suggesting that the delivery of caffeine in mouth and nasal aerosol sprays may activate sensors with neural links in the nose and provide a direct route for absorption in the lungs, although no research has examined this possibility (Wickham et al., 2018).

2.8.6 Caffeine Chewing Gum and BMX Performance

The rate and extent of a drug absorption can be influenced by its formulation. Chewing gum formulations have been assessed for some drugs including aspirin (Bousquet et al., 1992; Woodford et al., 1981) and nicotine (Benowitz et al., 1987) in previous early studies. The gum formulations offer several advantages over the tablet or liquid type. Firstly, most of the drug released from the gum through mastication is believed to be absorbed via the buccal cavity. Absorption through the buccal cavity is faster due to its extensive vascularization. Secondly, as speed of delivery is dependent on the onset of drug action, a faster absorption results in a shorter duration for a dynamic response. Lastly, drugs absorbed via the buccal cavity bypass intestinal and hepatic first-pass metabolism, which may occur in the intestines or liver when absorbed through the gut (Kamimori et al., 2002).

Novum (1997) reported the preliminary evidence of faster absorption rate of caffeine when delivered by gum compared with tablet, where about 85% of the caffeine dose is released in the initial 5 min of chewing. In this method, most of the caffeine can be absorbed via the oral mucosa therefore its absorption could occur faster. In another study by Kamimori et al. (2002), absorption rate, time to peak concentration, and peak concentration of three doses (50, 100, and 200 mg) of caffeine, delivered by gum versus capsule, were highlighted. Each condition had a separate group of 12 healthy male subjects who used less than 300 mg caffeine/day. Their results supported the faster absorption rate in gum compared with capsule. Time to reach the maximal caffeine concentration was also faster in the gum condition (44 - 80 min) versus the capsule condition (84 - 120 min). However, the maximal caffeine concentrations between capsule and gum conditions were not different at each of the three doses. When examining the 200-mg dose, a significantly faster rate of absorption with the gum was seen, as a large increase in plasma caffeine concentration occurred between 5 and 15 min. The largest increases in caffeine concentration with the capsules were delayed until 25-35 and 35-45 min. A follow up study by the same authors showed that plasma caffeine levels were maintained and increased in a dose-dependent manner with three repeated caffeine doses, each separated by 2 hours, when delivered in gum form with either 50, 100 or 200 mg of caffeine. Moreover, the gum and capsule formulations provide a near comparable amount of caffeine to the systemic circulation in the 100 and 200 mg caffeine (Syed et al., 2005).

A number of studies investigated the potential ergogenic effect of caffeinated gum administration on aerobic-based cycling. For example, (Ryan et al., 2012) administered 200 mg caffeine via two sticks of caffeinated chewing gum to physically active males, college-age at either 35 or 5 min pre-exercise, or 15 min into cycling at 85% VO_{2max} to exhaustion (~30-35 min). Endurance performance was not improved following consumption of the caffeinated gum at any of the administration times (-35, -5, and +15 min). In a follow-up study, Ryan et al. (2013) administered caffeinated 300 mg gum, or non-caffeinated gum, on well-trained male cyclists at either 120, 60 or 5 min pre-cycling at 75% VO_{2max} for 15 min, followed by a time trial, where 7 kJ/kg body mass of work was completed as fast as possible. Their results revealed caffeine improved cycling time trial performance only in the trial where the caffeine was administered 5 min before exercise. In another study, Lane et al. (2014) examined the effects of 3 mg/kg body mass of caffeine delivered in chewing gum to 12 well-trained males and 12 well-trained females during a time trial (females 29.35 km, males 43.83 km) lasting 50-60 min and simulated the cycling course at the 2012 London Olympic Games. Caffeinated gum was chewed with 2 mg/kg for 10 min, starting at 40 min pre-time trial, and another 1 mg/kg in the 10 min pre-time trial. The subjects also underwent two additional trials, one with beetroot juice (BRJ) and one with BRJ and caffeine. The results were similar for females and males, and caffeine ingestion in the caffeine trial alone and in the caffeine- BRJ trial significantly improved performance by 3–4% versus placebo, where BRJ has no significant effect on performance. Researchers continued to investigate the effect of caffeinated chewing gum on cycling performance. Paton et al. (2015) studied the effects of administering 200-300 mg caffeine via caffeinated gum at the 10-km mark of a 30-km time trial in 20 well-trained male and female cyclists. There was also a 0.2-km sprint (~15 s) at the end of each 10-km segment. Caffeine improved mean power by ~4% and increased speed by ~2% in the final 10-km and enhanced sprint power by 4% during the final sprint. Oberlin-Brown et al. (2016) examined 11 well-trained male cyclists who rode for 90 min at 63% $VO2_{max}$, followed by a 20-km time trial, on four occasions including caffeine, carbohydrate, and caffeine with carbohydrate. Caffeine was administered in 50-mg sticks of gum at the start of the time trial and completion of 5, 10 and 15 km, providing total dose of 200 mg. Their result failed to show any significant differences in time trial performance between conditions, with all times between 32:20 and 32:27 min:s. The method of providing caffeine in a small dose of (50 mg) only at the start of the TT and every ~8 min thereafter, might have limited the ergogenic effect of caffeine in this study.

The above-mentioned studies suggested that caffeine delivered by chewing gum in a dose of ~200–300 mg is ergogenic in well-trained male and females cyclists when delivered prior to or during an endurance event. However, there is less data available regarding the applicability of this administration method among sprint cycling events or strength/power performance. Paton et al. (2010) used caffeinated chewing gum in nine competitive male cyclists. Subjects completed four sets of 30 s maximal sprints (with 30 s of active recovery at 100 W), with five sprints/set. They cycled for 5 min at 100 W following sets 1 and 3. Following the second set, subjects cycled for 10 min at 100 W and caffeinated (240 mg) or placebo gum was administered. The rate of power output declined in sets 3 and 4 (ten sprints), but this was significantly reduced by the caffeinated gum compared with placebo. Bellar et al. (2012) studied caffeine effects on standing shot-put performance and reported a significant performance improvement following administration of 100 mg caffeine via chewing gum, in nine collegiate shot-put athletes. The subjects chewed the gum just before performing six throws (with 1 min rest between throws). The performance of the first throw and the overall performance of all six shot-put throws was improved following caffeine consumption. While a low dosage of caffeine seems to provide ergogenic aid for strength/power performance, it is important to consider if the habitual coffee drinkers could benefit from consuming a low dose of caffeine.

Evans et al. (2018) investigated the effect of caffeinated chewing gum (200 mg) on repeated sprint performance (RSA) in team sport athletes. They tried to find out whether low (< 40 mg/day) or moderate/high (> 130 mg/day) habitual caffeine consumption alters the ergogenic potential of caffeine. Eighteen male team sport athletes undertook four RSA trials using a 40-m maximum shuttle run test, which incorporates 10 × 40 m sprints with 30 s between the start of each sprint. Their results revealed that low habitual caffeine consumers (< 40 mg/day) experienced a 5% reduction of sprint performance decrement following caffeine consumption. The author concluded that habitual caffeine consumption modulates the ergogenic potential of caffeinated chewing gum for high-intensity exercise performance. In practical terms, ingestion of caffeinated chewing gum may be of value to team sport athletes, when rapid caffeine absorption and/or a low dose of caffeine is desirable, such as for pre-match or half-time ingestion.

More recently, Dittrich et al. (2019) analysed effects of 300 mg caffeine, delivered by caffeinated chewing gum, on endurance running tolerance and neuromuscular function of 12 trained male runners. To quantify neuromuscular fatigue of the knee extensor muscles, the maximal voluntary contraction associated to surface electromyographic recording and the twitch interpolation technique were assessed before and immediately after the tests. Their result showed that caffeine significantly improved exercise tolerance by 18%. Neuromuscular responses decreased similarly after time to exhaustion in both exercise conditions; but athletes in the caffeine condition were able to run a longer distance. Dittrich et al. (2019) concluded that caffeine seems to have a neuromuscular contribution to performance improvement, as athletes were able to run a longer distance with the same neuromuscular impairment. Ranchordas et al. (2019) determined whether a low dose of 200 mg caffeine in gum improves performance in a battery of rugby-specific tests. In their study seven male university-standard rugby players performed three countermovement jumps, followed by an Illinois agility test, 6 × 30m repeated sprints, and the Yo-Yo IR-2 test, where each test was separated by short rest periods. Their results supported the positive effects of caffeine on repeated sprint ability by demonstrating a greater resistance to fatigue during the 6 × 30 m repeated sprint test. Players demonstrated 3.6% improvement in countermovement jump and there was a 14.5%.improvement on the Yo-Yo IR2 performance.

In summary, caffeine in chewing gum can be effectively administered at doses up to 200 mg, and higher with repeated dosing. Caffeine delivered via chewing gum is absorbed quicker through the buccal mucosa compared with capsule delivery and absorption in the gut, although total caffeine absorption over time is not different. Delivering caffeine in chewing gum improved endurance cycling performance, and there is limited evidence that repeated sprint cycling and power production are improved (Wickham et al., 2018). Considering BMX as an intermittent sprint cycling sport, where riders require quick recovery between successive laps, applying caffeine via gum can potentially provide ergogenic effects on BMX riders' power production and overall race performance. However, to date, there is no published study to examine this hypothesis and BMX coaches and riders required more scientific evidence.

Overall, reviewing the literature highlighted the current gaps in scientific reports within the BMX cycling discipline. To provide sufficient background knowledge and valid scientific guidelines for BMX coaches and riders, it is essential to first highlight different aspects of this sport. When the both physical and physiological demands of BMX racing are described, using other aspects of sport science including nutritional supplementation and cognitive training could be used to improve riders' performance. Hence, applying a multidisciplinary approach will lead to a greater understanding of factors influencing riders' success and the efficacy of using different methods to enhance riders' performance.

Chapter 3

Study 1: Prediction of Track Performance in Competitive BMX Riders Using Laboratory Measures

Published in the Journal of Science and Cycling, 2020

3 Study 1: Prediction of Track Performance in Competitive BMX Riders Using Laboratory Measures

3.1 Foreword

This chapter is modified from a published article in the Journal of Science and Cycling on December 2020.

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Physical and physiological parameters measured in the laboratory are widely used by sport scientists to evaluate athletic performance and establish their training intensities. Body size and composition of many sportsmen have long been accepted as important factors in the performance of strength and motor tasks. Anthropometrical dimensions have been related to work output, recognising the potential significance in influencing attained levels of performance. Therefore, a considerable amount of information is available concerning the relationship of body structure and body composition to athletic performance. In the sport of BMX, data regarding riders' anthropometry and physique is limited and riders and coaches require more detailed information on the impacts of anthropometric features on BMX cycling performance.

As in cycling, performance is determined by physical output in direct interaction with a mechanical devise. Consequently, anthropometric parameters need to be considered in relation to the bike set-up. It has previously been shown that sprint cyclists are significantly heavier and stronger, and have larger chest, arm, thigh and calf girths than endurance cyclists (Craig et al., 2001). Successful cycling performance is also determined by a low relative body fat percentage, as additional body fat adds to the mass of the body without contributing to its force or energy producing capabilities (Mujika et al., 2001). This assertion also applies in BMX where riders are required to navigate obstacles and perform frequent jumps. Additional anthropometrical information would be helpful for coaches in selecting new riders and planning training programs to monitor riders muscle mass and body fat.

The review of Literature in Chapter 2 reveals the current lack of comprehensive reporting on the key physical features of BMX riders measured in the laboratory, and their potential influence on track performance. Therefore, the purpose of this Chapter is to provide practical data on the physical and physiological demands of BMX riders. This data will assist BMX coaches to have a better understanding of laboratory testing and design more specific off-season conditioning training programmes, as well as, providing normative data for use in talent identification processes.

3.2 Abstract

Identifying key physiological factors is essential in cycling; however, the unique nature of BMX decreases the validity and transferability of research findings from other cycling disciplines. Therefore, this study highlighted the physical and physiological characteristics of BMX riders that could influence track performance. Fifteen sub-elite BMX riders (male n = 12; age 18.3 ± 3.3 and female n = 3; 17.7 ± 5.7 years) undertook a battery of laboratory tests on three different occasions, including body composition, upper and lower body strength, flexibility, sprint and aerobic capacity measures. On a separate day, participants completed three full lap sprints separated by 15 min recovery between each sprint on an outdoor BMX track. Correlation and multiple linear regression analyses were performed to develop predictive models of performance across the laboratory tests and time trial time. The final model indicated power-to-weight ratio, relative back-leg-chest strength and arm span explained ~87% of the variability in finish time (adjusted $R^2 = 0.87$, $p < .01$). These findings highlighted the importance of a multidimensional approach for developing BMX time trial performance. Coaches should prioritise these variables in their training programs and selection of future talents. However, further physiological and biomechanical investigation is needed to validate current findings, particularly among elite riders.

KEYWORDS: peak power, BMX time trial, physiological demand, anthropometry

3.3 Introduction

Bicycle Motocross (BMX) is a relatively new Olympic sport since 2008, which is built on the premise of fast racing around off-road tracks on a bicycle smaller and lighter than a road bike or mountain bike. A BMX race over a 300-400m dirt track begins with the drop of the starting gate, after which up to eight riders pedal down a 5-8m slope. Riders then face several large jumps, banked turns, and smaller jumps in quick succession. In a BMX race, riders combine the cycling periods with technical non-pedalling periods known as manualling and pumping in which the upper body manoeuvres the bike. It is believed that both physiological and technical proficiency of riders contribute to race performance and riders' success (Rylands et al., 2017a).

Given the high technical and physical demands of BMX, previous research highlighted the importance of gaining the front position of the race group by the end of the first jump. This gives riders a distinct advantage to best navigate the upcoming obstacles and contribute with a faster finish time (Cowell et al., 2012b). To gain the front position, BMX riders attempt to apply a maximum power effort using the leverage and strength of their upper and lower body (Herman et al., 2009; Mateo et al., 2011; Rylands et al., 2014). Factors that could affect power output such as gear ratio (Rylands et al., 2017b), optimal cadence (Rylands et al., 2017c), and the maximal torque and cadence relationship (Debraux et al., 2013; Gardner et al., 2007) have also been investigated. Despite this, research of physiological demands and performance predictors are scarce, and BMX coaches require more specific research guidelines (Rylands et al., 2019).

Identifying key performance indicators is considered an important step to increase the efficacy of training programs. Bertucci et al. (2011) evaluated the relationship between laboratory measures, including Counter Movement Jump (CMJ), Squat Jump (SJ), seated and standing 30 s Wingate sprints, with subsequent race performance. Their results demonstrated a moderate relationship between power output and 80m sprint from a stationary start on levelled ground. However, this research was void of ecological validity. For instance, the race performance was measured only to the end of the first straight section (75m) and not over the whole track length; therefore, some findings may be missed by negating the rest of the race distance. In addition, with BMX being an intermittent cycling activity, where only 30-40% is devoted to pedalling, a 30s Wingate test may not be a good predictor of BMX performance (Cowell et al., 2011). Furthermore, while lower body power output was significantly associated with overall performance, success in BMX racing might also be influenced by factors other than just lower body power. For instance, riders' anthropometry (Grigg et al., 2017), muscular strength (Cowell et al., 2012b), and aerobic capacity (Louis et al., 2013).

BMX race analysis showed that ~70% of race time is spent jumping, coasting, or pumping (Cowell et al., 2011). Rylands et al. (2017a) showed that upper body pumping technique could improve finish time by 20% compared to non-pumping technique. Furthermore, Baker et al. (2001) stated that upper body strength significantly contributes to cycling peak power. Their study demonstrated that the intensity of the electrical activity recorded for the forearm musculature during sprint cycling was similar to that recorded during a maximum voluntary handgrip contraction. By pulling the handlebar, the centre of body mass is maintained at a constant vertical level, so that leg extension can be directed to pushing down on the pedals and facilitate the acceleration phase of performance (Dore et al., 2006).

Based on race movement pattern, it could be argued that overall muscular strength and the anthropometric profile of riders could improve leverage and offer functional advantages to BMX riders. Given the limited data available on the physiological demands of BMX racing, a holistic approach to identifying contributing factors to riders' performance seems most appropriate. This information could assist coaches in prioritising specific components of training for annual periodization and selecting future talents. Therefore, the purpose of the present study was to investigate the relationship between anthropometrical features and laboratory-based assessments of strength and power, with track performance.

3.4 Methods

3.4.1 Participants

Fifteen sub-elite BMX riders (12 males and 3 females; age: 18.3 ± 3.3, 17.7 ± 5.7 years; height 177 ± 5.8, 164 ± 3.6 cm; mass 69.2 ± 6.4, 67.8 ± 13.9 kg; body fat percentage (BF%) 13.3 ± 4.4, 26 ± 7.5; muscle mass 34.4 ± 3.2, 28.8 ± 1.6 kg; training experience 7.5 ± 2.5, 6.4 ± 2 years for males and females respectively) volunteered to participate in this study. All participants were informed about the study protocol and potential risks and provided written consent by the Declaration of Helsinki. Parental consent was also obtained for participants under the age of 18. This study was approved by the Human Ethics Committee of the University of Canterbury.

3.4.2 Design

In this cross-sectional study, the relationships between laboratory results and track performance were investigated using multivariate analysis over three different occasions. Firstly, participants had a familiarisation session of all laboratory testing procedures, as well as an anthropometric measurement. The following day, in the second laboratory session, maximal strength and cycling sprints were tested. Finally, 48 hours later, participants' aerobic capacity was tested. The track performance was measured one week later and described as the time taken to complete three all-out efforts on a 342m outdoor BMX track.

3.4.3 Anthropometric Assessment

Body mass (Seca Quadra 808 digital scales, Birmingham, UK), height (Seca 213 stadiometer, Birmingham, UK), arm span, hand dimensions (Lufkin W606PM anthropometric tape, SPARK, USA), and sum of seven skinfolds including triceps, subscapular, biceps, supraspinale, abdominal, thigh and medial calf (Harpenden Callipers Holtain, Crymych, UK) were assessed by a level two anthropometrist following the International Society for the Advancement of Kinanthropometry (ISAK) testing protocols (Marfell-Jones et al., 2012).

Muscle mass and BF% were determined using Bio-electrical Impedance (Inbody 230, Seoul, Korea). Its validity and reliability have been approved by Von Hurst et al. (2016). The somatotypes of participants were assessed according to the Heath-Carter method (Carter et al., 1990) using the Somatotype 1.2.6 program (MER Goulding Software Development, Geeveston, Australia).

3.4.4 Strength Assessment

Handgrip strength (HGS) was measured using a digital dynamometer (Jamar Plus Digital-Dynamometer, Chicago, USA) according to the American Society of Hand Therapists (Fess et al., 1981). Participants held a dynamometer in their hand with the arm held straight and maximally squeezed the dynamometer for three seconds. The maximum strength of the three attempts for each hand was recorded (Mathiowetz et al., 1984).

Back-Leg-Chest strength. A calibrated Back-Leg-Chest (BLC) strength dynamometer (Mentone, Victoria, Australia) was used to assess isometric muscle strength. The length of the chain was adjusted according to the participants' height with their knees and hips flexed slightly and with their lower back in an appropriate lordotic curve. Participants lifted in a vertical direction with a continuous isometric contraction the knees, hips, and lower back extensors. After demonstration and familiarization, three attempts were performed, each followed by a 30-second rest period. The best of the three attempts was recorded (Ten Hoor et al., 2016).

Maximal leg press, leg extension and bench pull strength tests (1-RM). A one repetition maximum test (1-RM) was used to estimate the maximal strength of bench pull, leg press and leg extension using a cable machine. Prior to testing, a warm-up of 6 to 10 repetitions at approximately 50% of the participants estimated strength was undertaken. The 1-RM test was initiated two minutes post-warm-up. Using the protocol employed by Brzycki (1993), participants attempted to lift each weight a maximum of 10 times. If 10 repetitions were achieved, a higher weight was tested following a 5-minute recovery. Whereas when a participant was only able to complete less than 10 repetitions, this number was entered into the maximum repetition calculations.

1-RM = 100 * load rep / (102.78 – 2.78 * Rep)

Where: load rep = workload value of repetitions performance in kg.

Rep = number of repetitions performed.

Leg power tests. The correct technique for SJ and CMJ were demonstrated and explained to each participant by a qualified biomechanist. The SJ tests were performed in an upright standing position with hands on the hips and flexed knees. This position was maintained for three seconds before participants jumped as high as possible, without any counter-movement action. The CMJ started with an upright standing position with hands unrestricted. The participants were encouraged to bend their knees to approximately 90° and use their arms to achieve the maximum height with no delay at their lowest position (Daneshfar et al., 2018). After a standardized warm-up of 2-3 repetitions of both SJ and CMJ, participants were asked to perform three jumps with a passive recovery of 1min between each jump. The highest jump of the three attempts was recorded. Participants were instructed to repeat any incorrectly performed jumps.

Laboratory Leg Power Assessment. Each participant performed three 10 s standing cycle sprints on a Wattbike Pro (Giant 2015, Nottingham, UK) which was calibrated according to the manufacturers' guidelines. The air and magnet resistance was set at level 1. Through the use of a load cell, Wattbike calculates force that cyclist applies through the cranks onto the chain at 100Hz. Power output is then calculated as the sum of all of the force applied to the chain. The highest peak power of the three attempts was recorded, as well as the average 10 s power, max cadence, time to peak power, minimal power, and fatigue index. The bar height and stem length were adjusted to each participant's preferred position, while the seat was set at the lowest position so it would not interfere when performing each sprint. Each participant performed their usual warm-up, which included both seated and standing short cycling sprints. Participants were encouraged to reach maximal power as fast as possible while performing each sprint from a standing stationary position using their preferred leg in the lead position. A rest period of 10 min was employed between each sprint (Gardner et al., 2007).

3.4.5 Maximum Aerobic Capacity ($\dot{V}O_{2max}$)

An incremental intensity bike test, undertaken to exhaustion, was used to determine $\dot{V}O_{2max}$. Following a 6-min warm-up at 100 W, power was increased by 30 W per minute until volitional exhaustion occurred, with participants choosing their preferred cadence. During the test, oxygen uptake ($\dot{V}O_2$), minute ventilation (VE), and respiratory exchange ratio (RER) were continuously measured breath-by-breath with a gas exchange analyzer (K5, Cosmed, Italy) which was pre-calibrated in accordance with the manufacturer's instructions. To determine $\dot{V}O_{2max}$, these three conditions were required: a plateau in $\dot{V}O_2$ despite an increase in power output, an RER above 1.1, and a heart rate (HR) above 90% of the participants' age-predicted maximal HR. Peak $\dot{V}O_{2max}$ was taken as the highest sampled average of the 30 s reading (Howley et al., 1995).

3.4.6 On Track Sprint Assessment

One weeks after completing their laboratory testing, participants were tested at the Christchurch BMX track, in New Zealand. Prior to testing, they performed a structured self-paced warm-up consisting of 4-6 standing short sprints. Three full lap time trials were then undertaken using the same BMX bike (gear ratio of 43/16). The track included a 5m high start ramp and a standard electronic start gate was employed. Lap time was recorded using two pairs of photocells (NEOtm Swift Performance, Queensland, Australia) positioned at the start gate and on the finish line. A 15-minute passive recovery was undertaken between each of the three time trials, and the fastest finish time of three time trials was recorded.

Blood lactate. Blood lactate concentration ($mmol \cdot L^{-1}$) was measured using a Lactate Pro2 analyzer (Arkray, Kyoto, Japan). A drop of blood was analysed from a finger prick was taken before warm-up (baseline value) and 3 min after the sprint tests (Tanner et al., 2010).

3.4.7 Statistical Analyses

Data were analysed using SPSS 25 (SPSS, An IBM Company, Amarouk, NY) and presented in mean ± SD. All variables were assessed for normality using the Shapiro-Wilk test. The Pearson's correlation coefficients and simple linear regression models were used to assess the relationship between the physical and physiological lab measures (independent variable) with the BMX finish time (dependent variable). It was also used to screen for independent variables to be included in the multiple linear regression model (Table 3.1). Forward stepwise multiple linear regression was conducted to identify the best model. In addition, the typical error of estimate and 95% Confidence Limits (CL) were used to describe predictive accuracy.

Table 3.1 Dependent and selected independent variables.

Dependent Variable	
Time to finish	time to completion of the time trial (s)
Selected independent variables	
Arm span	distance between the middle finger of each hand while the arms are outstretched (cm)
BF%	percentage of whole-body fat component (%)
Muscle mass	muscle mass (kg)
Relative leg press 1RM	one repetition maximum ($kg \cdot kg^{-1}$)
Relative bench pull 1RM	one repetition maximum ($kg \cdot kg^{-1}$)
BLC strength 1RM	one repetition maximum (kg)
Maximal HGS	hand grip strength (kg)
SJ	squat jump
power-to-weight ratio	power-to-weight ratio ($W \cdot kg^{-1}$)
Maximum cadence	cadence at peak power ($revs \cdot min^{-1}$)
$\dot{V}O_{2max}$	maximum oxygen capacity ($ml \cdot kg^{-1} \cdot min^{-1}$)

3.5 Results

Variables were normally distributed and descriptive data for lab and track performance is presented in Table 3.2. Pearson's correlation coefficients were significant between finish time and BF% (-0.727), endomorphic value (0.763), relative back strength (0.725), SJ (-0.730), and maximum cadence (-0.756), respectively (Table 3.3).

Following the identification of collinear variables, those variables (e.g. height, sit and reach, relative leg extension) that could not be retained in any models were omitted from the results. Forward multiple regression was performed for finish time with anthropometrical, and physiological variables. No violations of the assumption of linearity, homoscedasticity, and outliers were observed (Table 3.4).

The strongest model to predict the BMX time trial performance displayed a good fit (adjusted $R^2 = 0.867$; $p < .001$). This model utilised three independent variables: arm span, relative BLC strength and power-to-weight ratio which, when taken together, were responsible for 87% $F(3, 11)$ of the explained variability in the finish time of the time trial (Table 3.5).

Table 3.2 Descriptive statistics of the lab and the BMX track (mean ± SD).

	(Male, N=12)	(Female, N=3)
Somatotype and Anthropometric		
Endomorph	2.6 ± 0.4	5.3 ± 1.8
Mesomorph	4.9 ± 1.1	4.4 ± 1.7
Ectomorph	2.5 ± 0.8	1.6 ± 1.0
Arm span (cm)	178.7 ± 8.4	161.0 ± 5.8
Maximal hand dimension (cm)	22.4 ± 1.2	19.3 ± 2.1
Flexibility and Laboratory Strength		
Sit and reach (cm)	14.8 ± 5.8	18 ± 1
Leg extension 1RM (kg)	117.2 ± 13.0	83 ± 24
1RM relative leg extension ($kg \cdot kg^{-1}$)	1.7 ± 0.1	1.2 ± 0.2
1RM bench pull (kg)	62 ± 12.5	36 ± 9.9
1RM relative bench pull ($kg \cdot kg^{-1}$)	0.9 ± 0.1	0.5 ± 0.1
1RM leg press (kg)	177. 6 ± 30	125.7 ± 87.0
1RM relative leg press ($kg \cdot kg^{-1}$)	2.5 ± 0.3	1.7 ± 1.1
Maximal HGS (kg)	46.4 ± 5.6	31.3 ± 4.7
BLC strength (kg)	145.7 ± 20.0	101 ± 10
Relative BLC strength ($n \cdot kg^{-1}$)	2.1 ± 0.2	1.5 ± 0.2
CMJ (cm)	54.7 ± 10.7	32.3 ± 0.7
SJ (cm)	40.3 ± 6.3	24.67 ± 0.6
Laboratory Bike Test		
Peak power (W)	1220 ± 177	837 ± 138
Power-to-weight ratio ($W \cdot kg^{-1}$)	17.6 ± 1.8	12.5 ± 1.2
Average power (W)	1071 ± 165	718 ± 109
Relative average power ($W \cdot kg^{-1}$)	15.5 ± 1.9	10.7 ± 1.4
Maximum cadence ($revs \cdot min^{-1}$)	152 ± 10	125 ± 8
Time to peak power (s)	0.8 ± 0.6	0.7 ± 0.3
Minimal power (W)	948 ± 143	649 ± 60
Relative minimal power ($W \cdot kg^{-1}$)	13.7 ± 1.6	9.8 ± 1.7
Fatigue Index (a.u)	27.2 ± 7.5	18.8 ± 8.8
$\dot{V}O_{2max}$ ($ml \cdot kg \cdot^{-1} \cdot min^{-1}$)	43.3 ± 5.8	35.0 ± 5.3
RPE	9.7 ± 0.4	8.7 ± 0.6
Resting blood lactate ($mmol \cdot L^{-1}$)	2.2 ± 0.5	2.5 ± 0.7
Post 3 min blood lactate ($mmol \cdot L^{-1}$)	10.9 ± 2.7	9.5 ± 1.1
BMX Track Performance		
Finish time (s)	36.39 ± 0.70	40.71 ± 0.80
HR on the track (% of HR Max)	88.5 ± 3.9	85.2 ± 3.7

Table 3.3 Pearson correlation coefficient matrix.

	TTF	AS	BF%	MMS	RBP	RLP	DHG	RBLC	SJ	PWR	MCad	$\dot{V}O_{2max}$
AS	-0.676 †	-										
BF%	0.727 †	-0.472	-									
MMS	0.629*	0.783 †	-0.536	-								
RBP	-0.645 †	0.435	-0.525 *	0.657 †	-							
RLP	-0.543 *	0.583*	-0.065	0.388	0.529*	-						
DHG	-0.699 †	0653 †	-0.264	0.510	0.607 *	0.808 †	-					
RBLCS	-0.725†	0.303	-0.681 †	0.561 *	0.592 *	0.191	0.516 *	-				
SJ	-0.730 †	0.434	-0.464	0.522	0.678†	0.487	0.536*	0.544*	-			
PWR	-0.868 †	0.459	-0.636 *	0.568 *	0.749 †	0.395	0.475	0.644 †	0.786 †	-		
MCad	-0.756 *	0.767	-0.515 *	0.680 †	0.567 *	0.518	0.585 *	0.603 *	0.541 *	0.642 †	-	
$\dot{V}O_{2max}$	-0.647 †	0.304	-0.264	0.463	0.463	0.404	0.593 *	0.672 †	0.522 *	0.655 *	0.534 *	-

TTF: Time to Finish; AS: Arm Span; BF%: Body Fat Percentage; MMS: Muscle Mass; RBP: Relative Bench Pull; RLP: Relative Leg Press; DHG: Dominant Hand Grip; RBLC: Relative Back-Leg-Chest Strength; SJ: Squat Jump; PWR: Power-to-Weight Ratio; Mcad: Max Cadence; $\dot{V}O_{2max}$: maximum oxygen uptake normalized by body mass ($ml \cdot min^{-1} \cdot kg^{-1}$); *Significant at 0.05; † significant at 0.01

Table 3.4 Multiple regression model to predict time to finish of the simulate BMX time trial.

Anthropometric Variables				
Coefficient				
Predictor Variable	B [95%CI]	(β)	sr^2	
Arm Span	-0.161 [0.177, 0.055]	-0.334	0.039	
Body Fat%	0.136 [-0.016, 0.256]	0.502	0.183	
Model Summary				
Observation	R^2	*Adjusted* R^2	*F(3, 11)*	*p*
15	0.676	0.588	5.22	.005

Strength Variables				
Coefficient				
Predictor Variable	B [95%CI]	(β)	sr^2	
Relative Bench Pull	2.748 [-6.555, 4.756]	0.106	0.372	
Relative leg press	1.012 [-3.491, 1.606]	-0.165	0.021	
Relative BLC Strength	1.361 [-6.443, 0.170]	-0.466	0.133	
Maximal HGS	0.076 [-0.231, 0.168]	-0.200	0.004	
Model Summary				
Observation	R^2	*Adjusted* R^2	*F(4, 10)*	*p*
15	0.702	0.583	5.90	.011

Physiological Laboratory Variables				
Coefficient				
Predictor Variable	B [95%CI]	(β)	sr^2	
SJ	0.048 [-0.127, 0.086]	-0.092	0.003	
Power-to-Weight Ratio	0.176 [-0.777, 0.010]	-0.537	0.081	
Maximum Cadence	0.023 [-0.091, 0.10]	-0.312	0.054	
$\dot{V}O_{2max}$	0.051 [-0141, 0.088]	-0.091	0.005	
Model Summary				
Observation	R^2	*Adjusted* R^2	*F(4, 10)*	*p*
15	0.828	0.759	12.01	.001

Table 3.5 Final Performance Predictors.

Coefficient				
Predictor Variable	B [95%CI]	(β)	sr^2	
Arm Span	0.020 [-0.591, 0.162]	-0.349	0.096	
Power-to-Weight Ratio	0.079 [-0.106, -0.019]	-0.528	0.144	
Relative BLC Strength	0.726 [-3.190, -0.007]	-0.349	0.045	
Model Summary				
Observation	R^2	Adjusted R^2	$F(3, 11)$	p
15	0.896	0.867	31.55	.001

Unstandardised (B), and Standardised (β) Regression Coefficients, and Squared Semi-Partial correlations (sr^2) for each predictor in a regression model.

3.6 Discussion

To predict BMX performance, we used a multidimensional approach using laboratory-based measures. Notably, our findings displayed that across all the anthropometric, strength, and physiological categories, 87% of BMX time trial performance variation could be explained by power-to-weight ratio, relative BLC strength, and arm span. Coaches and cyclists can benefit from these findings as they demonstrate the factors that may influence BMX race result and could also be considered in talent identification processes.

The ability to generate maximum power in the first few seconds is vital for success in a BMX race. Rylands et al. (2014) analysed the 2012 UCI BMX World Cup series data and showed a strong correlation between the riders' position in the first 8–10 s of the race and their eventual finish line placing. In the current study, we applied a 10 s laboratory cycle sprint test to measure power. The strong correlation found between 10 s power-to-weight ratio and finish time supports the importance of power as a determinant of a rider's final position.

Power-to-weight ratio ensures absolute power is measured between riders regardless of body mass (Rylands et al., 2013). Riders with a high power-to-weight ratio can generate a substantially higher amount of force when a gate drops in the BMX race compared to riders with a lower power-to-weight ratio. Specifically, a higher rate of force development (RFD) allows riders to reach a higher level of force in the early phase of muscle contraction (Debraux et al., 2011b). This ability, when combined with quick reaction time, potentially assists a rider to have a greater chance of gaining the front position, which is a key factor for success in BMX racing.

Rylands et al. (2013) reported power-to-weight ratios of 21.29 ± 0.8 $W \cdot kg^{-1}$ and 16.65 $W \cdot kg^{-1}$ in 5 male and 1 female elite British BMX cyclists respectively, measured on a 50m track sprint test. The authors concluded that power-to-weight ratio might affect BMX riders' velocity, flight time, and distance travelled in the air while competing on a BMX track. The male BMX riders in the current study had a mean power-to-weight ratio of 17.6 ± 1.8 $W \cdot kg^{-1}$, in contrast with the female riders 12.5 ± 1.2 $W \cdot kg^{-1}$ for the three laboratory sprint tests. The highest laboratory correlation with finish time on the BMX track was related to power-to-weight ratio ($r = 0.87$; $p < .01$) and this was higher than the correlation ($r > 0.70$) found by Bertucci et al. (2011). In addition, the absolute male peak power value in our study was 123 W and 748 W lower than Spanish and French elite riders (1343 ± 68 W and 1968 ± 210 W) respectively (Bertucci et al., 2011; Mateo et al., 2011). The lower peak power output in our study may be related to a younger rider age or differences in testing procedures. It could also be explained by lower (regional) competitive level as previous research has found power of national-level riders is 28% higher compared to regional riders (Bertucci et al., 2007).

There was a significant negative correlation between finish time and BF% (r = -0.73, $p < .01$). Additionally, BF% was significantly correlated with power-to-weight ratio (r = -0.64, $p < .05$). Milašius et al. (2012) reported that BF% of the elite female BMX cyclist was ~23%, which was higher than elite track cyclists. In the current study, female riders had 26 ± 7.5 BF%, which was higher than both elite BMX rider and track cyclists. The excess fat component would almost certainly negatively affect power-to-weight ratio and influence race performance. Considering these findings, riders and conditioning coaches should monitor and maintain an optimal BF% to maximise power-to-weight ratio.

Generally, our findings were aligned with previous research that reported lower limb power (power-to-weight ratio) as an important factor in BMX (Cowell et al., 2012a; Debraux et al., 2013; Rylands et al., 2017b; Rylands et al., 2017c). Additionally, Debraux et al. (2011b) reported that results of CMJ, 8 s seated sprint cycle test, and 30 s Wingate were three performance-related factors (R^2 = 41 to 66%) during the 5 to 75 m of initial straightaway of the BMX track. Multiple factors contribute to BMX performance. We found that lower limb power, strength and anthropometric characteristics strongly predict variability of BMX time trial performance (adjusted $R^2 = 0.87$; $p < .001$). These results are essential for BMX coaches and practitioners while planning conditioning training to improve riders' performance.

Skeletal muscle strength is fundamental in many sports and exercise activities. The BLC strength test has been reported as a reliable measure for overall muscular strength (Ten Hoor et al., 2016). There are similarities between the BLC test, BMX movement patterns, and muscular recruitment across the entire BMX time trial. In particular, at the start of a race before initiating any movement, a riders' body posture is almost identical to the BLC strength test where hips are drawn towards the handlebars to keep their balance (Kalichová et al., 2013). Movement patterns during a BMX race demand high muscular strength in both the leg and back muscles. This can assist riders to have a powerful start, as well as to stabilize the bike during technical movements such as pumping, jumping in the entire race (Rylands et al., 2017a). In our study, relative BLC strength had the highest correlation (r = -0.73, $p < .01$) with BMX performance compared to other strength tests and hence, it was presented in the final model. Having higher relative BLC strength allows riders to apply greater upper body forces to the bike to generate more speed. It is worth noting that we examined the influence of different physiological measurements on BMX performance. However, further physiological and biomechanical investigation is needed to validate current findings, particularly among elite riders.

Arm span was significantly correlated with the finish time (r = - 0.68; $p < .01$) and appeared in our final model. The correlation between arm span and athletic performance has been investigated previously. Lockie et al. (2018b) reported that individuals with a longer arm span and a shorter leg length were able to reach peak power and velocity sooner during a deadlift. In a BMX race, riders with longer arms might be able to apply upper body force on the bike more efficiently compared to riders with shorter arms. It is also plausible that riders with longer arms can pump a further distance and generate more speed during the pumping technique where riders are neither pedalling nor jumping to increase their speed. However, another study reported that a longer arm span resulted in more work during a bench press as subjects need to move the bar further (Lockie et al., 2018a). Therefore, in a BMX race performing more work could potentially create more fatigue and negatively influence race performance. Cycling physiques vary between the different cycling disciplines. For instance, sprint cyclists are significantly heavier, and have larger chest, arm, thigh and calf girths than endurance cyclists (Craig et al., 2001). As the BMX bike dimensions do not vary, riders' height and arm span could affect mechanical efficiency and subsequently overall race performance. Further physiological and biomechanical investigation is required to measure the impact of arm span on power development and race performance in BMX to validate its actual influence. If confirmed, this finding could be considered by coaches and practitioners during the talent identification process, as arm span is dependent on genetics.

3.7 Practical Applications

This study has demonstrated that various factors can potentially explain BMX time trial performance. Our results suggest that coaches and practitioners should consider multiple characteristics when planning a training program. Namely, they should focus on short sprint power production, as this was the key component of the regression model for BMX finish time. In the current study, we only discussed the final and strongest predictive model, but other variables are still important. Factors including SJ, pull strength, and $\dot{V}O_{2max}$ could also be trained as they demonstrated a high correlation with finish time. It is apparent that individual body size could also be an important factor with a significant effect on BMX performance, and could assist the riders' selection and talent identification processes. In summary, our data presents specific aspects of BMX riders that should be targeted to maximise performance. We recommend that additional studies with more elite-level riders are undertaken to provide validity around these findings.

3.8 Limitations

There are several limitations which should be noted. The population of high-level BMX riders in the South Island is very limited, and including more elite level riders would increase the validity of the results. In addition to this, using more female riders in the study could provide comparative information around gender effects on BMX performance. Furthermore, using a specific BMX power meter on a real track will help to find the correlation between power produced in the lab condition and a simulated BMX time trial.

3.9 Conclusion

In conclusion, this study showed that power-to-weight ratio, relative BLC strength, and arm span explained 87% of the variability in BMX performance. We used a multidimensional approach to identifying contributing factors to BMX performance. This information can assist BMX coaches in prioritising specific components of training for annual periodization, as well as new riders' selection process.

Chapter 4

Study 2: Determinant Physiological Factors of Simulated BMX Race

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4 Study 2: Determinant Physiological Factors of Simulated BMX Race

4.1 Foreword

This chapter is derived from a published article in the European Journal of Sport Science on December 2020.

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The focus of sport research is to provide coaches and athletes with data to inform better practice and enhance results in competition. The structure of a competition has also been shown to alter the physiological characteristics associated with success. Therefore, in order to prescribe optimal training plans for a particular sport, a comprehensive understanding of the interaction between physical work executed during competition and the physiological response to that work is essential.

In BMX racing on the track, unlike the consistent work protocols administered in the laboratory to test riders, a highly varied work condition will apply. Significant periods of low cadence and low force exist during jumps sections while higher cadence and higher force periods are evident during the flatter or cornered sections. In addition, a competition day consists of several individual laps followed by 15-30 min recovery. This makes the BMX racing format a unique structure similar to repeat sprint performance but with longer recovery periods.

Despite the need for laboratory-based data, measuring riders' performance on the actual BMX track provides more valid and reliable data and lays out the physiological characteristics associated with optimal performance. In addition, when establishing normative performance profiles and identifying factors related to success, it is crucial to establish the physiological demands of the race. These data will help coaches to adapt their training program to target specific loads and intensity. By highlighting the key laboratory based performance indicators of BMX riders in Study 1, the aim of Study 2 was to examine the track demands during a simulated BMX time trial and to determine the metabolic pathways involved over multiple time trials.

4.2 Abstract

Evaluating the physiological demands of BMX cycling on a track provides coaches with the information required to prescribe more effective training programmes. To determine the relative importance of physiological factors during a simulated BMX time trial, 12 male riders (age 19.2 ± 3.5 years, height 1.76 ± 0.06 m, mass 68.5 ± 4.3 kg) completed a maximum aerobic capacity ($\dot{V}O_{2max}$) test in a laboratory, and a week later, completed six laps on a BMX track under simulated time trial conditions interspersed by 15 min passive recovery. Peak power, immediate post-lap $\dot{V}O_{2peak}$, blood lactate, and heart rate were measured in each lap. Peak power-to-weight ratio was significantly correlated with lap time, however, the strength of this association decreased each subsequent lap. Mean $\dot{V}O_{2peak}$ was greater than 80% of laboratory measured $\dot{V}O_{2max}$ in every lap, indicating a strong contribution of the aerobic energy system during BMX racing. This study also identified that mean blood lactate was significantly associated with lap time, which showed the importance of the anaerobic energy system contribution to BMX racing. Despite the short period of pedalling during BMX racing, both aerobic and anaerobic energy systems are important contributors to lap performance. Coaches should consider maximising both anaerobic power and aerobic capacity to improve riders' overall performance in multiple laps.

Keywords: peak power, $\dot{V}O_{2peak}$, blood lactate, cycling performance

4.3 Introduction

Understanding the physio-metabolic requirements of a sport enables coaches to prescribe targeted training programmes to maximise performance. Using laboratory assessments relative to field-based workloads, researchers have identified several performance indicators in Bicycle Motocross (BMX) (Bertucci et al., 2011; Daneshfar et al., 2020d; Rylands et al., 2015). However, laboratory measures have poor correlations with BMX racing on the track, limiting the transferability of the results (Daneshfar et al., 2020a; Rylands et al., 2019). A better understanding the physiological demands of BMX racing will assist coaches to focus on the key factors that have the potential to enhance on track performance.

A BMX competition usually involves a qualification series, quarterfinals, semi-finals, and the final. Riders who are eliminated in qualification series perform a minimum of three laps and those who progress to the final, complete six laps or more depending on the number of riders (Zabala et al., 2011). Each lap typically lasts between 30-40 s followed by 15-30 min recovery between laps. As the countdown to the next lap begins, riders line up behind an electronic start gate awaiting the starting signal (Zabala et al., 2011). The start gate drops after the signal and riders pedal from a standing position down a 5-8 m ramp ("Part VI: BMX Rule Book," 2019), before navigating a series of four straights with jumps separated by berms (u-bend corners).

BMX is considered an intermittent sport and includes repeated high-intensity cycling sprints (Zabala et al., 2008) followed by non-pedalling periods. The ability to perform repeated sprints relies on the contribution of the aerobic and anaerobic energy systems (Tomlin et al., 2001). Due to a significant contribution of the anaerobic energy system in high-intensity cycling sprints, a significant increase in blood lactate concentration has been reported (Zabala et al., 2011). This increase in lactic acid concentration may also lead to reduced power output and increased finish time in the latter laps.

Maintaining performance across repeated sprints requires greater ability to reduce blood lactate, regulate pH, and importantly, replenish phosphocreatine (PC) stores (Porter et al., 2019). Considering BMX racing as a repeated sprint event, data is limited regarding the relative importance of metabolic pathways and the consistency of power output over successive laps. To the authors' knowledge, only one study has examined the metabolic response of simulated BMX time trial with elite riders (Louis et al., 2013) and reported that high $\dot{V}O_{2peak}$ (94 ± 1% of $\dot{V}O_{2max}$) could be responsible for 54% of the variation in lap performance. This relatively high contribution is possibly due to the carryover from the initial high anaerobic demands of an explosive start, and the isometric work of the upper limbs throughout the lap. Louis et al. (2013) did not investigate the correlations between performance variables of lap time, peak power, $\dot{V}O_{2peak}$, and blood lactate. Consequently, the relationship between these factors and BMX performance remained unknown.

Currently, there is a lack of empirical data on the metabolic pathways and physiological demands of repeated BMX laps. If collected, this information will assist with the development of more effective training programmes and better monitoring of riders' progress. Accordingly, this study aimed to identify the physio-metabolic factors of BMX racing in sub-elite riders. It was hypothesised that lap time would significantly correlate with peak power output and lap $\dot{V}O_{2peak}$. Furthermore, it was hypothesised that blood lactate responses would be positively associate with peak power production and post laps $\dot{V}O_{2peak}$.

4.4 Methods

4.4.1 Participants

Twelve nationally competitive male BMX riders participated in this study. Mean ± standard deviation (SD) of subjects' demographic data were: age 19.2 ± 3.5 years, height 1.76 ± 0.06 m, body mass 68.5 ± 4.3 kg. Subjects received written and verbal instruction regarding the risks and nature of the procedure. Subjects were also asked to complete a training history questionnaire (developed by the author), which identified that all subjects had been actively involved in BMX riding and racing for 5.0 ± 1.5 years. The average amount of on-track training time was 4.5 ± 1.5 h each week. This study was approved by the University of Canterbury's Human Ethics Committee (approval number: HEC 2018/83) and was carried out in accordance with the Declaration of Helsinki. Before commencement, all subjects completed the Physical Activity Readiness Questionnaire (PAR-Q) and provided their written consent. Parental written consent was obtained for subjects under 18 years old.

4.4.2 Experimental Design

For testing the hypothesis, the correlations between $\dot{V}O_{2max}$, BMX lap $\dot{V}O_{2peak}$, lap time and power production were examined. To measure $\dot{V}O_{2max}$, a laboratory-based incremental intensity bike test to exhaustion was performed. This was followed a week later by a simulated BMX time trial on a track, involving six laps interspersed by 15 min of passive recovery between each successive lap. Subjects were familiarised with the equipment and testing protocols before completing the experimental testing sessions (Figure 4.1).

4.4.3 Anthropometric Assessment

Stature was measured to the nearest centimetre with a wall-mounted stadiometer (Seca 213 stadiometer, Birmingham, UK) and mass was determined to within ± 0.1 kg with a digital weighing scale (Seca Quadra 808 digital scales, Birmingham, UK).

4.4.4 Maximum Aerobic Capacity ($\dot{V}O_{2max}$)

An incremental maximal cycle test was carried out on a Watt Bike Pro (Giant 2015, Nottingham, UK) which was calibrated according to the manufacturers' guidelines. The subjects performed a 6-minute warm-up at 100 W; power was then increased by 30 W per minute until volitional exhaustion occurred. The cadence and air resistance were set for each individual based on the manufacturer's guidelines for a maximal ramp test.("Wattbike guideline book for maximal ramp test.pdf," 2019) Heart rate (HR) was monitored using a GarminTM (Garmin®, Olathe, USA). Metabolic data were obtained during the test using a previously validated portable telemetric metabolimeter system Cosmed K5 (Cosmed, Rome, Italy), which was pre-calibrated following manufacturer's instructions. Before each test, the gas analyser was calibrated using a high-precision gas mixture (5.06% CO_2 and 16.02% O_2) and the spirometer with a 3-litre syringe (Hans Rudolf, Kansas City, MO, United States). Subjects were assumed to have achieved $\dot{V}O_{2max}$ if the following three criteria were met: 1) a plateau in $\dot{V}O_2$ despite an increase in power output, 2) a Respiratory Exchange Ratio (RER) above 1.1, and 3) > 90% of HR_{max} obtained during the test (Howley et al., 1995). $\dot{V}O_{2max}$ was considered to be the highest average 30 s of oxygen uptake. Peak power output was considered as the average cycling power recorded over the one minute period equating with $\dot{V}O_{2max}$ (Gastin et al., 1994; Howley et al., 1995).

4.4.5 Simulated BMX Time Trial

The simulated time trial was carried out one week after the laboratory session on an outdoor track (342-meter and 28° gradient ramp), with three berms, four straights, and several technical jumps on each straight section. The simulated time trial was conducted in summer at a temperature of 19 ºC, humidity of ~45%, and side wind speed of ~5 km/hr. Subjects were instructed to perform a warm-up to their preferences, consisting of 4-6 standing short laps. Each subject was asked to complete six full laps individually and as fast as possible from a 5-meter high start ramp using a standard electronic start gate. All subjects rode the same BMX bike (gear ratio of 43/16) fitted with an SRM BMX power meter crank (Schoberer Rad Messtechnik, Welldorf, Germany). The power meter had an eight strain gauge and a 175 mm crank arm. Prior to each test, the power meter was configured in combination with the SRM instructions. Data was downloaded using Power Control8 software (PC8DeviceAgent). To include the effect of subjects' weight on power performance, peak power-to-weight ratio (PWR) was calculated.

During the lap, HR was continuously monitored by the Garmin HR chest strap. The percentage of maximum HR obtained in the laboratory test was used for data analysis. Subjects undertook a 15-minute passive recovery between each lap as they typically undertaken in BMX race. The percentage lap time (LT) decrement (%Dec) was calculated using the following formula: %Dec = $\left(\frac{(LTmean - LTbest)}{LTbest}\right) \times 100$, where LT_{mean} = mean lap time and LT_{best} = fastest lap time of the 6 BMX laps.(Oliver, 2009) Lap time was measured using two sets of photocells (NEOtm Swift Performance, Queensland, Australia) positioned at the start gate and on the finish line.

Oxygen uptake. The expired gases were analysed immediately after each lap using a Cosmed K5. A mask was fitted on each subject's face covering both their nose and mouth as soon as they crossed the finish line within the first 5 s post lap. Data was recorded during the first minute of recovery. The oxygen recovery curve was measured during the first 20 s to predict peak oxygen uptake ($\dot{V}O_{2peak}$) reached during the lap (Jalab et al., 2011; Louis et al., 2013). Following testing, the subjects' rating of perceived exertion (RPE) was recorded using the 0–10 Borg scale ranging from very very light (0) to exhaustion (10) (Borg, 1998).

Blood lactate. Blood lactate concentration (mmol·L^{-1}) was measured using a Lactate Pro2 analyser (Arkray, Kyoto, Japan), where a finger prick was taken immediately before (baseline value) and three minutes after each lap (Tanner et al., 2010). The blood lactate response (BLr) was defined as the difference between pre-lap and post-lap lactate measures.

4.4.6 Statistical Analyses

Before analysis, data were tested for normality using a Kolmogorov–Smirnov test and all data were normally distributed. The Statistical Package for the Social Science (SPSS 25) was used to accomplish statistical procedures (SPSS, An IBM Company, Amarouk, NY) and the results are expressed as mean ± SD. Pearson Product-Moment correlations were used to assess the relationships between $\dot{V}O_{2max}$ from the incremental test and BMX time trial dependent variables including lap time, peak power, blood lactate, and $\dot{V}O_{2peak}$. While dependant variables were compared between successive laps (independent variable) using a repeated-measures ANOVA. Significant main effects were further analysed by Bonferroni adjusted post-hoc test. The level of significance was set at $p \leq 0.05$ except in the instance of a Bonferroni correction in which, 0.05 was divided by the number of comparisons.

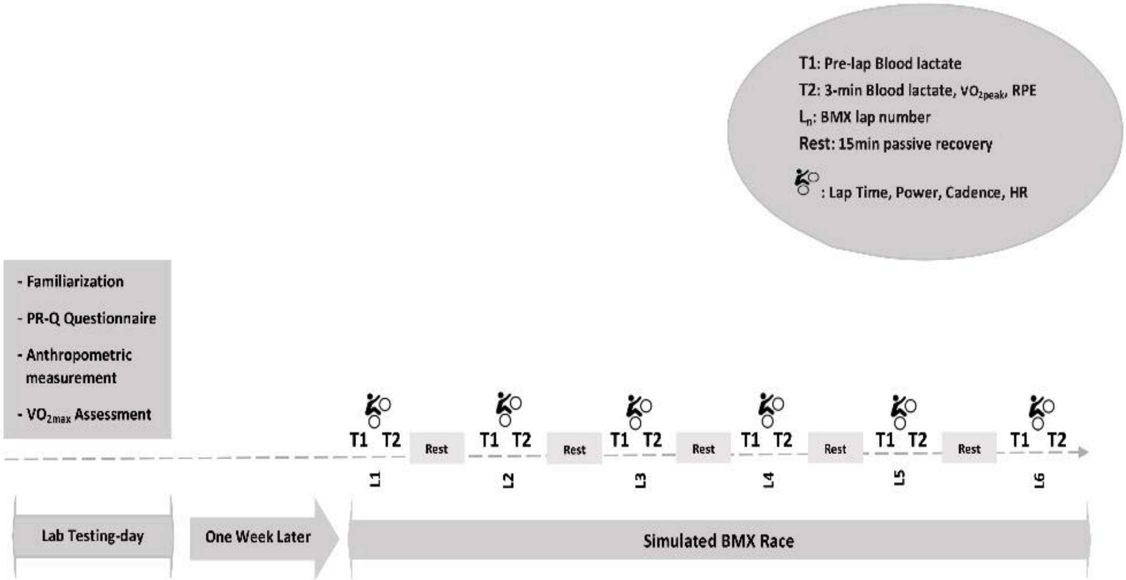
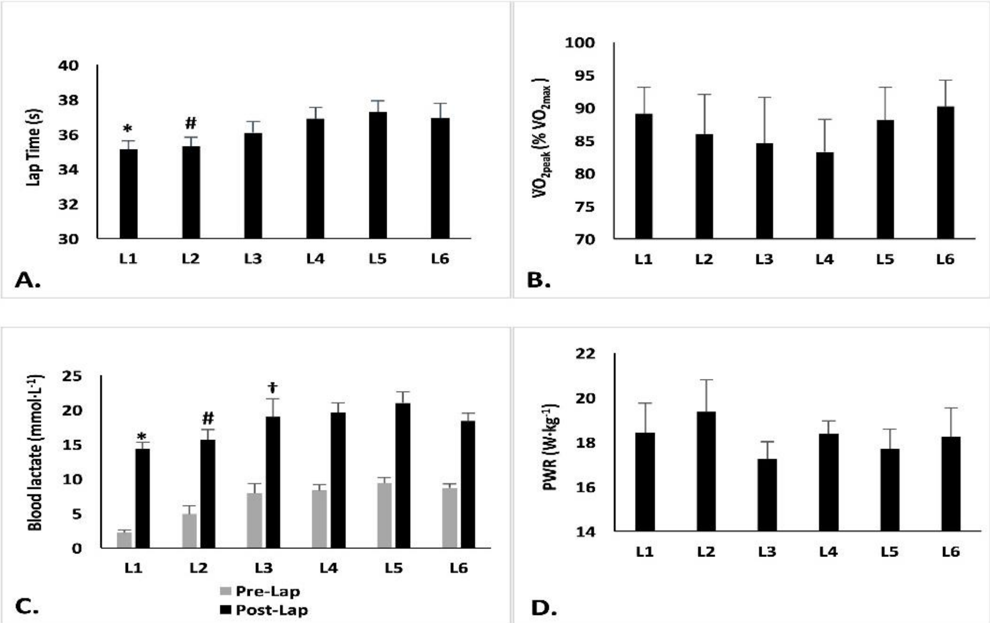


Figure 4.1 simulated BMX time trial study design.

4.5 Results

The lap time increased throughout the simulated time trial (riders got slower each lap), showing a significant effect of lap number, where L1 was faster than L2, L3, L4, L5, L6 and L2 faster than L4, L5, L6 $F(5, 55) = 29.39$, $p = 0.004$. $\dot{V}O_{2peak}$ reached more than 80% of $\dot{V}O_{2max}$ in each lap (mean 87 ± 4% $\dot{V}O_{2max}$), but there was no significant effect of lap number on $\dot{V}O_{2peak}$ $F(5, 55) = 3.41$, $p = 0.421$. As shown in Figure 4.2, there was a significant effect of lap number $F(5, 55) = 22.94$, $p = 0.012$ on post-lap blood lactate values (mean = 16.4 ± 2.5 $mmol \cdot L^{-1}$).



*****Significant difference p < 0.01, between L1 and L2, L3, L4, L5, L6

Significant difference p < 0.01, between L2 and L3, L4, L5, L6

† Significant difference p < 0.01, between L3 and L4, L5, L6

Figure 4.2 Simulated BMX time trial (Lap1-6) selected physiological components.

The correlation between blood lactate and subjects' performance are presented in the scatter plot (Figure 4.3A). Overall, we found a significant association between mean blood lactate response (BLr) with mean lap time (r = 0.61; p = 0.004), mean PWR (r = -0.68; p = 0.002) and mean $\dot{V}O_{2peak}$ post laps (r = -0.70; p = 0.001). In addition, as presented in Figure 4.3B, lap time was inversely correlated with subjects' mean PWR (r = -0.81, p = 0.003) as well as mean $\dot{V}O_{2peak}$ after laps (r = -0.72, p = 0.001).

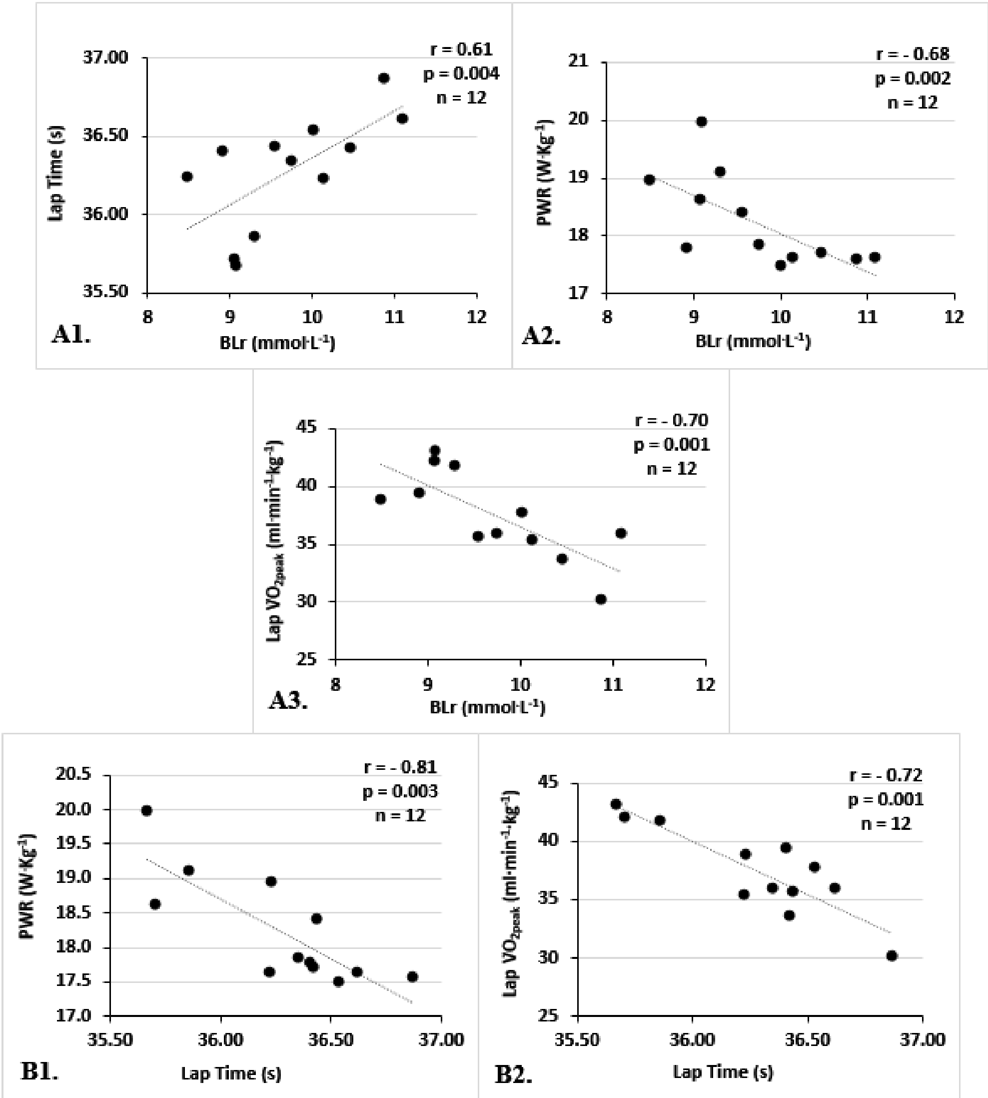


Figure 4.3 Scatter plot between mean BLr and **A1**) mean lap time, **A2**) mean PWR, and **A3**) mean lap $\dot{V}O_{2peak}$.

Mean lap time and **B1**) mean PWR, **B2**) mean lap $\dot{V}O_{2peak}$.

BLr: difference blood lactate of pre and post laps, **PWR:** peak power-to-weight ratio of Lap1-6, **Lap Time:** finish time of Lap1-6, **Lap $\dot{V}O_{2peak}$:** $\dot{V}O_{2peak}$ measured post Lap1-6.

The correlations between each lap time and physiological parameters are shown in Table 4.6. LT_{best} was significantly associated with PWR (r = -0.70, p < 0.003), $\dot{V}O_{2peak}$ (r = -0.67, p < 0.005), BLr (r = -0.67, p < 0.002) and $\dot{V}O_{2max}$ (r = -0.76, p < 0.004). LT1 and LT2 showed a similar pattern and a significant correlation with PWR, $\dot{V}O_{2peak}$, and BLr. LT3 revealed no correlation with PWR, but a significant correlation with $\dot{V}O_{2peak}$ and BLr. LT4 and LT5 were significantly correlated with PWR, $\dot{V}O_{2peak}$, BLr and $\dot{V}O_{2max}$. Going through the final stage of the time trial, LT6 had poor correlation with PWR, but showed significant association with $\dot{V}O_{2peak}$, BLr and $\dot{V}O_{2max}$. There was no significant correlation for RPE and HR_{max} values with time trial time performance.

Table 4.2 Relationship between BMX lap times with physiological variables.

	PWR	**$\dot{V}O_{2peak}$**	**BLr**	**%HR_{max}**	**RPE**	**$\dot{V}O_{2max}$**
LT_{best}	-0.70*	-0.67*	0.67*	-0.25	0.35	-0.76**
%Dec	0.16	0.15	-0.37	0.20	-0.12	0.16
LT1	-0.70*	-0.54*	0.53*	-0.27	0.32	-0.35
LT2	-0.70*	-0.55*	0.55*	-0.02	0.45	-0.48
LT3	-0.38	-0.64*	0.56*	-0.35	0.14	-0.31
LT4	-0.60*	-0.66*	0.63*	-0.30	0.11	-0.55*
LT5	-0.53*	-0.69*	0.65*	-0.15	0.43	-0.68*
LT6	-0.38	-0.70*	0.68*	-0.09	-0.01	-0.79**

LT_{Best}: fastest time over 6 laps ; **%Dec**: the percentage in a sprint decrement for the 6 laps; **LT1-6:** mean time to finish Lap1 to Lap6; **PWR:** mean peak power-to-weight ratio of 6 laps; **$\dot{V}O_{2peak}$:** mean $\dot{V}O_{2peak}$ of 6 laps; **BLr**: mean difference blood lactate of pre and post laps; %**HR_{max}**: mean percentage of maximum heart rate; **RPE:** mean rating of perceived exertion of 6 laps; **$\dot{V}O_{2max}$**: mean maximum aerobic capacity measured in the lab; ******: correlation is significant at the 0.01 level; *****: correlation is significant at the 0.05 level.

4.6 Discussion

This study found that: **a**) BMX lap time was significantly correlated with mean PWR but the strength of this association decreased as successive laps were performed. **b**) Subjects demonstrated a high contribution of aerobic metabolism during laps and showed a significant correlation with mean lap times. This association indicated an incremental trend. **c**) Mean BLr was significantly correlated with mean lap time, and the correlation between BLr and time in each lap was stronger in the latter laps. According to our results, despite the short (~35s) cycling time in each BMX lap, both aerobic and anaerobic energy systems were associated with performance.

Several reports have shown that peak power is one of the most important factors related with success in BMX racing (Daneshfar et al., 2020c; Grigg et al., 2017; Rylands et al., 2017b). In line with our results, Bertucci et al. (2011) reported an inverse correlation (r = -0.67) between PWR and sprint time in national level BMX riders over 75m of the track (Initial Straightway). More recently, Daneshfar et al. (2020a) reported that PWR of sub-elite riders 18.3 ± 2.3 $W \cdot kg^{-1}$ was significantly correlated with time trial time (r = -0.68). In the current study, PWR presented a strong correlation with the lap time (r = -0.81; p = 0.003). As the peak power occurred during the first 30 m of the track, our results were in agreement with Rylands et al. (2014) who concluded that riders' start performance were significantly correlated with the final lap placement. We measured riders' performance under simulated time trial condition, which increases the validity and transferability of the results.

The results of the present study suggest that lap time has a significant correlation with post lap $\dot{V}O_{2peak}$ (r = -0.72; p = .001). Our results reflect those of Louis et al. (2013) who also used backward extrapolation to predict time trial $\dot{V}O_{2peak}$ amongst BMX riders. The authors concluded that elite BMX riders reach a very high relative $\dot{V}O_2$ during every lap (Mean $\dot{V}O_{2peak}$ 94 ± 1% of $\dot{V}O_{2max}$). A slightly lower value for mean $\dot{V}O_{2peak}$ reached in our study (87 ± 1% $\dot{V}O_{2max}$), might be due to the differences in riders' aerobic capacity or their competitive level, which enabled them to perform at a greater percentage of their maximum aerobic capacity. In addition, different equipment (K4B2) and application of this equipment to measure $\dot{V}O_{2peak}$ in their study might potentially be another reason for different results. In the present study, we set out with the aim of determining the importance of metabolic pathways in BMX time trial performance. An incremental relationship was found between post laps $\dot{V}O_{2peak}$ with each individual lap time (R1-R6). In the early laps, riders' performance was more strongly associated with anaerobic metabolism and sprint capacity; in contrast, during later laps, their performance relied on aerobic metabolism. These results are in line with other researchers who have reported significant correlations between $\dot{V}O_{2max}$ and repeated-sprint ability (RSA) performance (Bishop et al., 2006; Pareja-Blanco et al., 2016). In general, a more developed aerobic capacity enabled the riders to recover faster and as a result, riders' performance declined to a lesser degree. It is worth noting that to measure post-lap VO_2, there was some delay (> 5 s) from crossing the finish line to wearing the mask, therefore the first few seconds of oxygen recovery curve data might be missing and potentially influence the VO_{2peak} values.

Our results found a high metabolic demand in a BMX time trial, especially of the first 10-15 s, where riders generated a high power output resulting in a large rate of force development. The high metabolic demands are extended due to the continued technical work and isometric efforts of the upper body, throughout the entire lap (Rylands et al., 2017a). In line with previous studies that have investigated the impact of aerobic metabolism on RSA, oxidative metabolism can improve performance by increasing PCr resynthesize between multiple sprints (McGawley et al., 2015). These findings assist coaches and riders to better understand the importance of aerobic capacity in BMX racing, and consider this factor when developing training programmes. Further studies should aim to re-evaluate the importance of aerobic capacity in BMX racing in athletes of all levels.

In the current study, the mean blood lactate values after each lap was 16.44 ± 1 mmol·L^{-1} (mean BLr = 10 ± 0.6 mmol·L^{-1}). This is in agreement with those obtained by Louis et al. (2013) who reported a high blood lactate concentration (14.5 ± 4.5 mmol·L^{-1}) in elite BMX riders after six laps. More recently, Petruolo et al. (2020) also showed that the lactate levels in elite riders reached 12.9 ± 1.6 mmol·L^{-1} following four laps of simulated BMX time trial. The authors concluded that the performance of the subsequent lap could be affected as post-lap blood lactate values did not completely recover over 30 min rest periods. The high lactate concentration reflects high anaerobic glycolysis across the BMX laps and confirms the importance of the anaerobic energy system in repeated sprints bouts. Our results also presented a strong correlation between mean BLr with lap time (Figure 4.3A). This may raise the assumption that subjects, who have achieved faster BMX lap time, are those who had higher lactate concentrations post laps as a result of the greater work intensity, as well as better lactate clearance capability during recovery. Lactate removal is an oxygen-dependent process and it is known that endurance-trained individuals have a greater ability to remove lactate following intense exercise (McLester et al., 2008). Therefore, even if aerobic fitness did not directly improve a single lap time due to greater anaerobic energy demand, it is plausible that greater oxidative capacity contributes to improved cycling performance in successive laps.

The results of the current study provide further support for the hypothesis that the ability to repeatedly perform anaerobic efforts is an important determinant of maximal anaerobic performance (McGawley et al., 2015). Similar to RSA, one of the most suggested factors that may impair performance is the accumulation of acidosis (increased hydrogen ions H^+). Prior studies induced alkalosis in subjects using bicarbonate to explore ways of improving performance (Zabala et al., 2008; Zabala et al., 2009a), but failed to report any positive effects on riders' sprint performance. More recently, Peinado et al. (2019) did not report any ergogenic benefit of bicarbonate on BMX performance consisting of three laps separated by 15 min of recovery. In the current study, 61% of lap time variation was explained by BLr. To better understand the role of acidosis during BMX laps, it is essential to consider the impact of aerobic fitness and recovery approaches undertaken after laps. These are known to influence the lactate removal and acidosis level. BMX coaches should also consider sprint interval training programmes inducing high metabolic stress to improve repeated laps via greater improvements in H^+ regulation, natural buffering system, and developing aerobic capacity (Gist et al., 2014; Ramos-Campo et al., 2018).

In summary, according to the results of this study, despite the short cycling time in each BMX lap, both aerobic and anaerobic energy systems were associated with riders' performance. BMX coaches and practitioners may consider the importance of these factors when designing conditioning programmes. While focusing on improving riders' lap time, peak power, and technique, they should also develop riders' aerobic capacity as it plays a critical role in overall BMX performance. Sprint interval training can be a useful method for improving successive BMX laps via greater improvements in H^+ regulation, natural buffering, and developing aerobic capacity. The current approach will prove useful in expanding our understanding of how different physio-metabolic variables affect BMX performance. Future research should consider using a greater number of subjects to compare the lap demands of female and male BMX riders, as well as comparing elite and national-regional riders' performance.

Chapter 5

Study 3: Power Analysis of Field-Based Bicycle Motor Cross (BMX)

Published in the Open Access Journal of Sports Medicine, 2020

5 Study 3: Power Analysis of Field-Based Bicycle Motor Cross (BMX)

5.1 Foreword

This chapter is derived from a published article in the Open Access Journal of Sports Medicine, published online July 2020.

Daneshfar, A., Petersen, C., Gahreman, D., & Knechtle, B. (2020). Power analysis of field-based bicycle motor cross (BMX). Open access journal of sports medicine, Volume 2020:11 Pages 113-121. https://doi.org/10.2147/OAJSM.S256052

Power output is an important indicator of performance and is widely acknowledged as a direct measurement of exercise intensity. With the introduction of commercially available cycling power-monitoring tools, power output is easily measured during racing and training. Despite this, limited information exists using these systems in the sport of BMX.

In the first two investigations (Chapter 3 and 4), the demands of BMX racing were explored and the findings highlighted the importance of riders' ability to produce maximal power in both laboratory and track condition. BMX racing utilizes an entire range of performance dynamics, from no power generation to vigorous energetic efforts. Continuous pedalling is frequently interrupted due to the individual nature of BMX tracks, so it is important to monitor power output in simulated BMX time trials and to analyse the workload during different track sections. Many coaches and cyclists remain sceptical about the actual benefits of training based on power, and remain uncertain as to how to best implement the use of power meters as training tools. Therefore, the aim of this chapter was to characterise the power production profile of BMX riders, in addition to cadence and heart rate over the whole length of a BMX track and determine the workload performed during different track sections in a simulated BMX time trial.

5.2 Abstract

Power meter is a useful tool for monitoring cyclists' training and race performance. However, limited data is available regarding BMX racing power output. The aim of this study was to characterise the power production of BMX riders and investigate its potential role on time trial performance. Fourteen male riders (age 20.3 ± 1.5 years, height 1.75 ± 0.05 m, mass 70.2 ± 6.4 kg) participated in this study. Riders performed two time trials 15 min apart. An SRM power meter was used to record power and cadence. Cyclists' fastest time trial was used for the data analysis. Heart rate were recorded at 1-s intervals using a Garmin HR chest strap. Lap time was recorded using four pairs of photocells positioned at the start gate, bottom of the start ramp, end of first corner (time cornering), and on the finish line. There was a large correlation between time trial time and relative peak power (r = -0.68, $p < 0.01$) as well as average power with zero value excluded (r = -0.52, $p < 0.01$). Time trial time was also significantly associated with time cornering (r = 0.58, $p < 0.01$). Peak power (1288.7 ± 62.6 W) was reached in the first 2.34 s of the time trial. With zero values included, average power was 355.8 ± 25.4 W which was about 28% of peak power, compared to 62% when zero values were excluded (795.6 ± 63.5 W). Post-time trial analysis of power data might help cyclists recognize the need to apply certain strategies on cadence and power production in certain portions of a track, specially, at the start and around the first corner. BMX coaches must consider designing training programs based on the time trial intensity and power output zones.

Keywords: sprint cycling, cadence, heart rate, data binning

5.3 Introduction

Cyclists from a recreational to elite level use power meters to examine the power output profile of training and race performance (Passfield et al., 2017). For many scientists and coaches a simple power analysis consists of identifying peak power and time to peak power. However, for a more thorough evaluation of power from data output, the type of race, track condition, and quantifying variation in power output during the race should also be considered. For instance, in some sprint cycling events such as bicycle motocross (BMX), pedalling is intermittent throughout the race and consequently, riders' power production is sporadic.

A BMX lap typically lasts between 30-50 s in duration. Each BMX track is unique in shape and distance and ranges between 200-400 m in length, incorporating a variety of jumps, corners, and flat sections ("Part VI: BMX Rule Book," 2019). A BMX track can be categorized into three different phases. 1) Gate start acceleration phase, determined by the gradient of the ramp and the values of maximum power production. 2) Mixed central phase, where riders 'pump' without pedalling when tackling obstacles, and then, pedal maximally to maximise power or maintain speed. 3) Stamina phase, where riders try to maintain a high-power output and maximise speed by pedalling. Therefore, the stamina phase plays a significant role in the final performance (Mateo et al., 2011). These phases affect the BMX race technical and conditional requirements and reduce the options for applying power.

A number of studies suggest an association between peak power and BMX race performance (Bertucci et al., 2011; Daneshfar et al., 2020d; Grigg et al., 2017). These research studies mainly focused on measuring performance over the first phase of the track or short distance sprints. For instance, Rylands et al. (2013) were the first to use an SRM power meter system and evaluated velocity production. They compared the results of six elite BMX riders power production over a 50 m and 200 m flat asphalt surface with other cycling disciplines.

Riders in this study produced peak power of 1256 ± 276 (W), which was closer to the track sprinters and more than the power outputs of the endurance mountain bike riders. A major limitation with this kind of methodology is the lack of validity and transferability of the results, as they have not undertaken their research on an actual BMX track. The same applies for laboratory-based measures evaluating power production (Rylands et al., 2017c; Zabala et al., 2008). The laboratory results can evaluate the riders' power production capacity, but it is unknown whether this is repeatable on the track. Clearly, there is the need for a more valid method of measuring power output in BMX racing.

To the best of our knowledge, only Mateo et al. (2011) has evaluated power output under a BMX race condition. Their results showed that the average peak power applied in the BMX race was 85% of the laboratory-tested maximum power. These values decreased to 73% at the gate start and to 51% on the first straight. They concluded that the power profile of elite BMX riders is dependent on certain factors, including the phases and techniques of the race, and are significantly affected by the level of track difficulty. As track characteristics influence pedalling time and require multiple technical demands, power production varies through the race. Consequently, a more detailed analysis of power output data can determine how the volume and intensity of racing (and training) has been distributed.

Power output distribution can be described within a race or training session using time spent in designated data bins or zones. Data bins are generated using percentage total time spent within a power band. To present the data visually the bins can be plotted to produce a session histogram. Previous studies have used a data binning approach to investigate physiological responses during training and cycling competitions (Lucia et al., 1999). Ebert et al. (2005) used a similar comparison for two types of women's World Cup cycle road races and calculated the percentage of total race time spent within four data zones. Although simple, this method is excellent for the purpose of overall session comparisons. Due to the variable nature of the power output during BMX racing, the use of data binning transposes the complex stochastic power meter data into a simple, easy to interpret output for BMX coaches.

Despite such monitoring, many BMX coaches and cyclists remain uncertain about the actual benefits of training based on power, and how to best implement the use of a power meter as a training tool. Hence, the aim of the current study was to first, characterise the power production of BMX riders in time trials. It was hypothesized that cyclists' time trial times would be significantly correlated with time cornering and power output of the time trial.

5.4 Methods

5.4.1 Participants

Fourteen sub-elite male BMX cyclists (age 20.3 ± 1.5 years, height 1.75 ± 0.05 m, mass 70.2 ± 6.4 kg, and training experience 6.5 ± 1.5 years) volunteered to take part in this study. Those with any recent injuries or medical conditions were excluded from the study. All cyclists were informed about the study protocol and potential risks and provided written consent by the Declaration of Helsinki. Parental written consent was obtained for subjects under-18 years old. This study was approved by the University of Canterbury's Human Ethics Committee (approval number: HEC 2018/83).

5.4.2 Experimental Design

Before starting the time trial, all cyclists' body mass (Seca Quadra 808 digital scales, Birmingham, UK) and height (Seca 213 stadiometer, Birmingham, UK) were recorded. Each cyclist then followed a structured warm-up including 5-10 standing-start cycle sprints, and dynamic stretching. After 5 min rest, cyclists performed two all-out BMX time trials from a 5-

meter start ramp with a standard electronic start gate (Pro-Gate, Rockford, IL, USA). Cyclists had 15 min passive recovery between time trials and their quickest time trial was used for the data analysis.

5.4.3 BMX Track

The track performance was described as the time taken to complete one all-out effort on a 342-meter outdoor BMX track with a 28° descent and 5-meter start ramp, four straights with several technical jumps on each straight section, and three corners (Figure 5.1). The first straightaway is defined from where the start ramp meets the track surface till landing from the last jump. The second straightaway starts from the end of the first corner to where the rider landed from the last jump. The third straightaway is quantified as starting at the end of the second corner extending to the top of the final obstacle (small jump). The fourth and final straightaway begins as soon as the third corner is completed and extends to the finish line (Cowell et al., 2012a). This track hosts BMX national competitions in the South Island of New Zealand.

Figure 5.1 A view of the North Avon BMX track.

Time trial time assessment. Lap time was recorded using four pairs of photocells (NEOtm Swift Performance, Queensland, Australia) positioned at the start gate, bottom of the start ramp, end of first corner (Time cornering), and on the finish line (Figure 5.2).

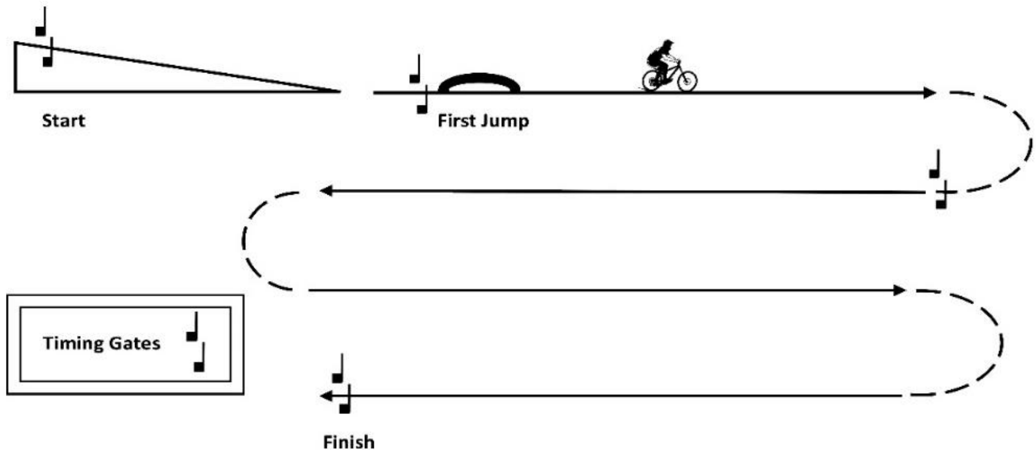


Figure 5.2 Schematic figure of the photocells positioning on the BMX track.

Power analysis. In the current study, the SRM (Schoberer Rad Messetechnik) training system was used to measure power output during the BMX time trial. SRM has been shown to be a valid tool for measuring power output during field conditions (Gardner et al., 2004). SRM measures the power directly at the crank arm with precision strain gauges attached to the inside of a deformable disk situated within the inner bolt circle of the crank arm. As force is applied to the cranks, the strain gauges convert this into a power value. The cadence is also assessed with every pedal revolution. This signal is then transmitted to a handlebar-mounted power controller. SRM has previously demonstrated to be a valid measure during field conditions over a range of power when compared with dynamic calibration (Gardner et al., 2004). For this test, the SRM system was set to record at 1-s intervals. Before each time trial, the zero offset of the power meter was re-entered into the power control unit in accordance with the manufacturer's guidelines. This offset zero was taken into account by establishing the actual output frequency of the cranks. The SRM power meter incorporated an eight-strain gauge and a 175 mm crank arm, which were attached to the BMX testing bike (gear ratio of 43/16). All the relative data including peak power and cadence was downloaded after time trials using Power Control8 software (PC8DeviceAgent).

Binning time trial power output. To describe the power output distribution within a time trial, the amount of time spent within chosen data bins was analysed. Data was then visually presented with the bins plotted as a session histogram (Ebert et al., 2005). The power bands were chosen to represent: 1) low intensity cycling (<100 W), 2) moderate peak power (100–300 W), 3) high intensity efforts (300–500 W) and sprints (>500 W).

Heart rate. During the time trial, Heart Rate (HR) was monitored using the Garmin HR chest strap (HRM-Dual™, USA). The heart rate monitor was sampling at a rate of 1-s intervals.

5.4.4 Statistical Analysis

Data are presented as mean ± standard deviation (SD) and statistical significance was set at $P \leq 0.05$. All statistical analyses were conducted using SPSS 25.0 (SPSS Inc., Chicago, IL, USA). Pearson's product–moment correlation coefficient was used to determine the relationship between time trial variables including, time trial time, time to peak power, power output, cadence, and HR. During non-pedalling phase, all cyclists recorded zero values for both power and cadence. Therefore, data for average power and cadence are presented with both included and excluded zero values.

5.5 Results

There was a significant correlation between race time and relative peak power (r = -0.68, $p < 0.01$) as well as average power with zero value excluded (r = -0.52, $p < 0.01$). Race time was also significantly associated with time cornering (r = 0.58, $p < 0.01$). In the current study average cadence was significantly correlated with relative average power (r = 0.68, $p < 0.01$). There were no statistically significant associations between HR and other race variables. Mean ± SD of the race variables are presented in Table 5.3.

Table 5.3 BMX time trial variables.

Variables	Mean ± SD 0-values excluded (0-values included)
Time	
Time trial time (s)	34.23 ± 1.21
Time to peak power (s)	2.34 ± 0.16
Time cornering (s)	12.14 ± 0.34
Power/Cadence	
Peak power (W)	1288.7 ± 62.6
Average power (W)	795.6 ± 63.5 (355.8 ± 25.4)
Relative peak power ($W \cdot kg^{-1}$)	18.3 ± 2.3
Relative average power ($W \cdot kg^{-1}$)	11.3 ± 1.4 (5.0 ± 0.9)
Peak cadence ($rev \cdot min^{-1}$)	131 ± 6
Average cadence ($rev \cdot min^{-1}$)	100 ± 8 (45 ± 5)
Heart rate ($beat \cdot min^{-1}$)	163 ± 2

5.5.1 Power Output

As presented in Figure 5.3, power values output fluctuated during the time trial. BMX cyclists' peak power (1288.7 ± 62.6 W) was reached in the first 2.34 s of the time trial. With zero values included, the average power was 355.8 ± 25.4 W which was about 28% of the peak power recorded in the time trial compared to 62% when zero value were excluded (795.6 ± 63.5 W). The Figure 5.4 also showed the distribution of power production throughout the time trial. While non-pedalling phase contributed for ~40% of the time trial time, cyclists generated high power (>500 W) ~35% of the time.

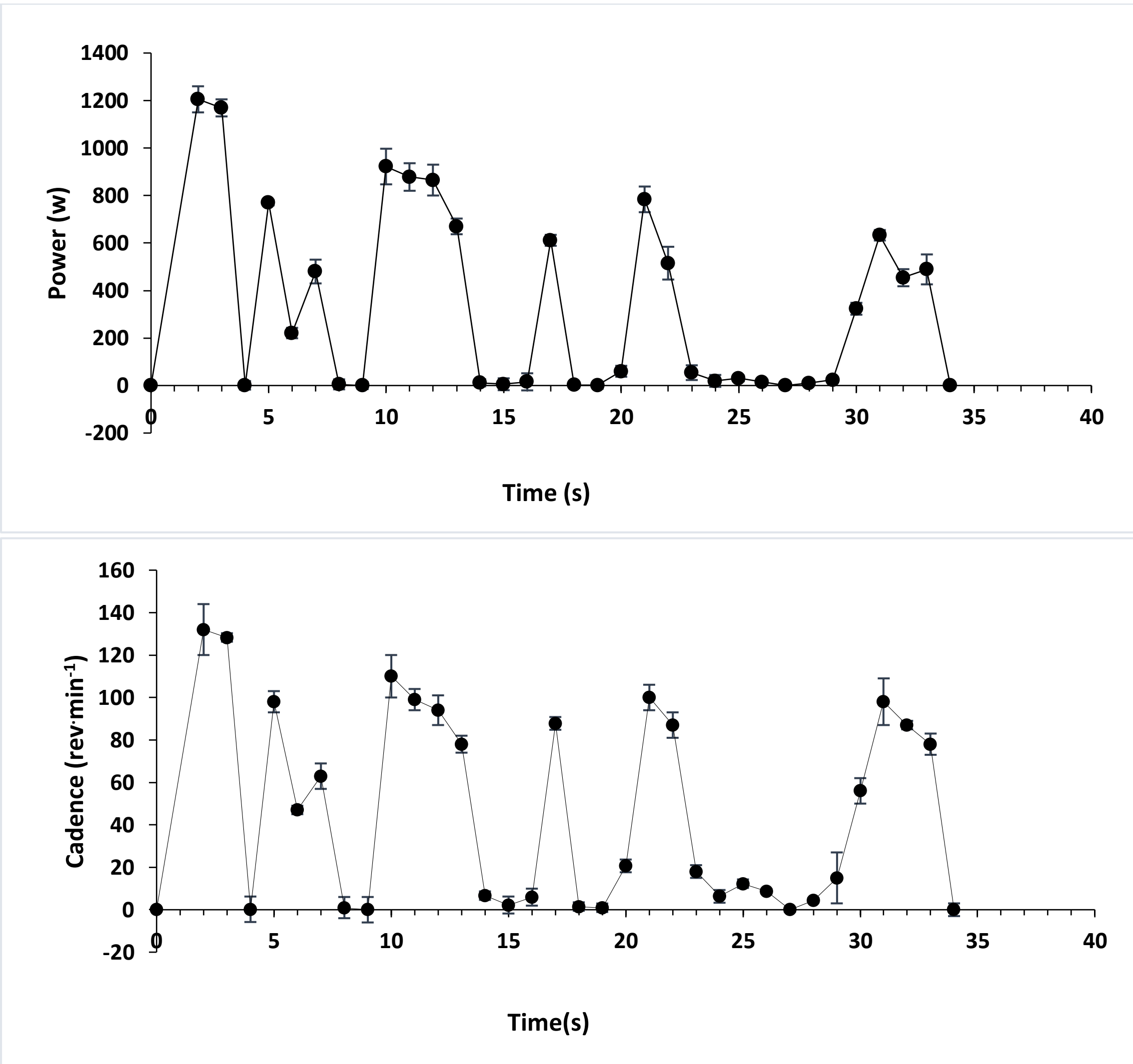


Figure 5.3 Mean ± SD power and cadence values recorded at 1-s intervals in the BMX time trial.

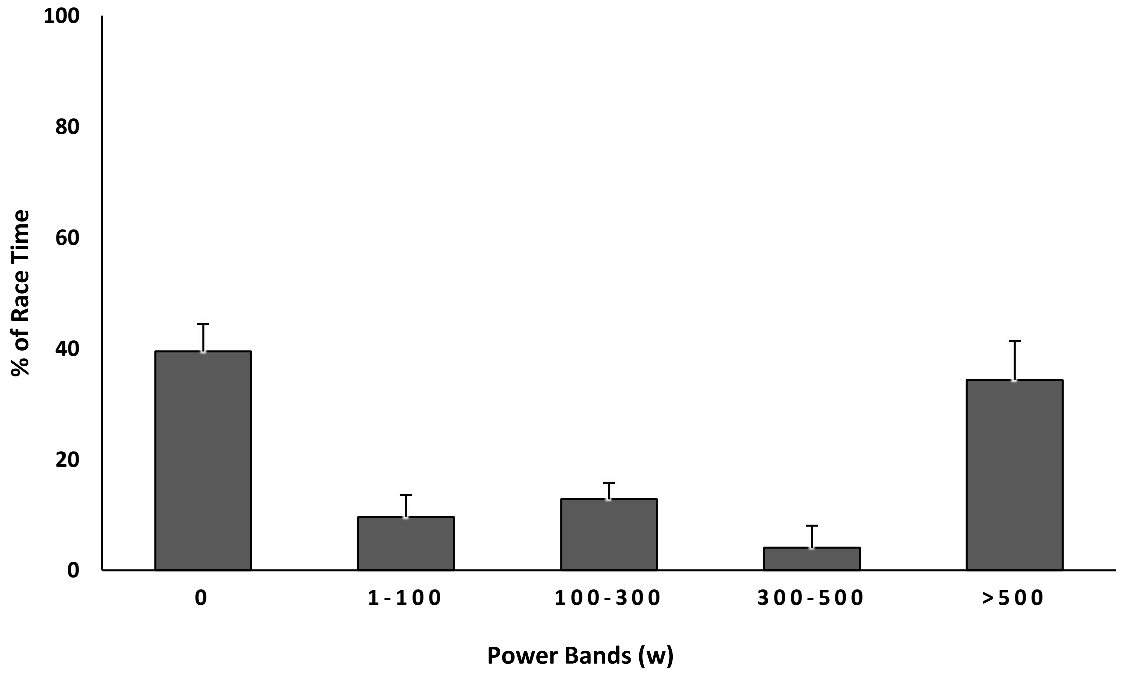


Figure 5.4 Mean ± SD power distribution in BMX time trial.

5.5.2 Cadence

Cadence displayed a similar pattern to the power profile, as peak cadence of 131 ± 6 rev·min^{-1} occurred at 2.13s of the time trial. Again, with zero values excluded, the average cadence fell to 100 rev·min^{-1}. With zero values included, the average cadence was 45 rev·min^{-1}, which equated to 22% of maximum cadence (Figure 5.3).

5.5.3 Heart Rate

HR reached its peak 163 ± 2 beat·min^{-1} after 20 s and remained at this level for the rest of the time trial. As shown in the Figure, BMX cyclists' time trial at ~80% of their maximum predicted HR (220-age).

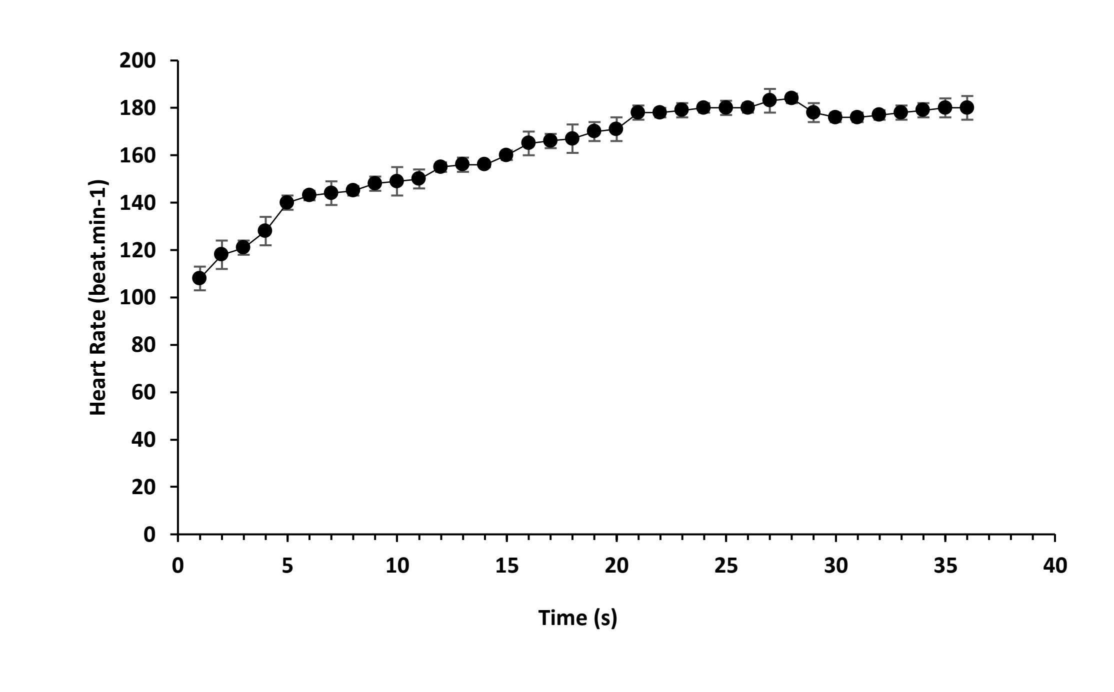


Figure 5.5 Mean ± SD heart rate values recorded at 1-s intervals in the BMX time trial.

5.6 Discussion

There are limited reports that have assessed BMX power performance over the course of a time trial. The present study was designed to analyse the power output of a simulated BMX time trial and evaluate any associations between cyclists' time trial time and power related variables on different parts of the track. Our results demonstrated a significant association between both peak and average power with time trial time. They also highlighted the importance of the first straight of a BMX track and its impact on overall time trial performance. Furthermore, the current study provides the first report on the power data binning in BMX cycling, showing the distribution of riders' power over the time trial period. Time-course power analysis in the current study confirmed the previous beliefs around intermittent nature of BMX racing (Rylands et al., 2019).

BMX cyclists in the current study reached a relative peak power of 18.3 ± 2.3 $w \cdot kg^{-1}$ which was significantly correlated with time trial time (r = -0.68, $p < 0.01$). This was in line with previous research highlighting peak power as an important determinant factor in BMX racing. Rylands et al. (2013) reported relative peak power of British elite male BMX riders over a 50 m flat surface 21.3 ± 0.8 $w \cdot kg^{-1}$. The lower values of relative peak power in the current study are potentially due to the recruitment of sub-elite riders. Additionally, as Rylands et al. (2013) measured performance over a flat surface and not on a BMX track, higher pedalling time resulted in greater power generation.

Zabala et al. (2008) reported peak power outputs of 1607 ± 310 W for Spanish elite BMX riders, which was 20% higher than the peak power achieved in the present study. It is worth noting that the results of Zabala and colleagues were derived from a Wingate test using a Monarck cycle ergometer, and the use of different power measuring equipment may limit transference between studies. Bertucci et al. (2011) reported the peak power values (1968 ± 210 W) of the French elite riders over an 80-m track sprint and concluded that, power output of the lower limb explained between 41 to 66 % of the performance during the initial straightaway of a BMX track. One study which measured power over an entire BMX track, on three different tracks, was conducted by Mateo et al. (2011). They measured maximum power of 1343 ± 68 W in an 8-second sprint test using a Power Tap power meter with national Spanish BMX riders. Peak power was 1144 ± 28 W with an average time to peak power of 1.42 ± 0.02 s. In the current study, BMX riders reached their peak power after 2.34 s, but generated 12% more power in the race compared to the Spanish riders. A possible explanation for these results may be the use of a different power meter, as well as testing on tracks with incompatible levels of difficulty.

Another important finding of the current study was that the average power (zero value excluded) showed a significant association (r = -0.52, $p < 0.01$) with the time trial time. In a

BMX race, pedalling is often prevented by jumps, curves, and other changes in the track, which affect power production. However, generating power in the track corners, or when pedalling is possible, would assist riders to maintain their speed and overcome the upcoming obstacles. Therefore, in addition to a powerful start, and generating maximum power in the first few seconds of the race, maintaining power and velocity is another critical factor in BMX racing. There is limited data available regarding the power profile of a BMX race. Only Mateo et al. (2011) has reported an average power of 329 ± 83 W for an entire BMX track (with zero values included), which was compatible with the results of the current study at 355 ± 25 W. On technical tracks, average power decreases as there is less opportunity for pedalling and more emphasis on pumping to navigate the technical sections. The average power of a race gives insight into the actual stress imposed by a given workload, since fluctuations in power are further affected by tactical considerations or track shape. Data obtained via racing with a power meter can be used to evaluate BMX performance, evaluate training and determine what changes could be made to a riders' program to enhance performance.

Time cornering in the current study demonstrated a positive correlation with riders' overall time trial time ($r = 0.58$, $p < 0.01$). Our data also showed that second peak power (72% of time trial average power) occurred when riders pedalled around the first corner, after an explosive power production at the start. Previous studies have highlighted the importance of the first straight in a BMX race, however, our data showed that time cornering is another important factor associated with overall race time. Cowell et al. (2012a) analysed the time trial event of the 2010 BMX World Championships and reported time cornering of 13.92 ± 0.42 s, while total time on the first straight was 9.16 ± 0.21. Authors concluded that in a BMX race, each section of the track requires a different skill set and performance on one section is likely to influence performance on subsequent sections. Based on our results, riders with faster time cornering were more likely to have a better overall race performance. While the initial power helps BMX riders to pick up the best position in the track, their pedalling performance in the first corner can minimize any loss in speed, and provides a chance to maintain their speed by generating more power.

The present study provides a deep understanding of BMX time trial power output distribution by data binning. Power production varies substantially in a BMX time trial. Riders spent ~35% of time trial time in the >500 W sprint zone highlighting the importance of anaerobic system contribution in a BMX time trial. On the other hand, the non-pedalling period of a time trial equated for ~40% of overall time trial time, as well as a period of very low power output (<100 W). Power production less than 100W are considered insignificant power output. The data binning strategy has been used in road racing previously, where Ebert et al. (2005) reported the power distribution of cyclists during the Women's World Cup in road races (from 1999 to 2004). Riders spent ~5% of the race time in the sprint zone, where ~45% of race time was under the peak power zone. One of the advantages of racing and training with a power meter is that it provides a simple way to precisely control overall training load. By continuously recording power output, the exact demands of each race can be more accurately quantified, and the intensity or duration (or both) of subsequent training sessions can then be modified. These findings help BMX riders have a clearer understanding of power profile in training and power production within a BMX time trial and the importance of >500 W sprint zone. BMX coaches should also consider training program with high metabolic stress levels such as high intensity interval training to improve repeated sprint performance in race (Ramos-Campo et al., 2018). Future research needs to provide data of the power profile of elite riders during international BMX competitions. This would give an insight into the fitness standards required to be competitive and successful at an elite level and may offer a screening tool for coaches and sport scientists in the talent identification processes.

Another finding presented in our study was the significant correlation between average cadence and relative average power (r = 0.68, $p < 0.01$). This demonstrated a similar pattern to the power profile during a BMX race. Cadence has been highlighted as one of the key factors contributing to power production and mechanical power output (Hurst et al., 2006). However, as BMX bikes are equipped with only a single gear, data regarding optimal cadence and peak power is contradictory. For instance, Herman et al. (2009) reported that the power cadence relationship (occurs in the first 1.6 s of a race) and could thus have an effect on BMX riders' finish line placing. Riders in this study reached a peak cadence of 212 ± 4 revs·min^{-1} and a peak power of 2087 ± 156 W. Debraux et al. (2011a) analysed peak power and cadence produced during the 80-m sprint test and reported an optimal theoretical cadence of 122 ± 18 revs·min^{-1} that elicited peak power. In a laboratory-based study, Rylands et al. (2017c) analysed the optimal cadence for peak power and time to peak power production, where each elite BMX rider completed three maximal sprints at a cadence of 80, 100, 120 and 140 revs·min^{-1}. These riders produced peak power (1105 ± 139 W) at 100 revs·min^{-1} and shortest time to power production was attained at 120 revs·min^{-1} in 2.5 ± 1.07 s. In the current study, riders' average cadence was 100 ± 8 revs·min^{-1}, however peak power was achieved at the higher cadence (131 ± 6 revs·min^{-1}). The reason for this is less technical sections of the track where riders can generate and maintain power and velocity by relying on cadence. However, during non-pedalling phases, the majority of time was spent with the pedals static, acting more as a support platform. Our data provided an in-depth analysis of cadence and power production compared to previous studies as we measured performance over an actual track. It is important for BMX coaches and riders to be aware of the crucial role cadence plays in a race and how it should influence training intensity and gear selection.

The present study has several limitations. Firstly, the small sample size of sub-elite BMX riders, most likely affected our statistical power. Future studies using a larger sample size of elite BMX riders are needed to confirm these findings. Secondly, it is important to monitor BMX performance over repetitive races (there are usually six races in a BMX tournament), and to compare this data with other physiological variables including the aerobic and anaerobic capacity. Finally, our power meter sampling rate was low and might have affected our power measurement. Using a power meter with a higher sampling rate in future research would help to accurately assess BMX power profile on the track.

5.7 Conclusions

Overall, this study strengthens the idea that power output is a critical variable in BMX race performance and should be measured over the whole track under race conditions. As power is highly variable in BMX racing, average power and peak power need to be analysed. Therefore, BMX coaches must consider designing training programs based on race intensity and power output zones. Post-race analysis of power data also helps cyclists recognize the need to apply certain strategies on cadence and power production in certain portions of the BMX track including start and first corner. Furthermore, such data provides insight into cyclists' relative strengths and weaknesses. Comparison of power profiles from race to race and their association with time may indicate whether fatigue or technical performance were responsible for a drop in power.

Chapter 6

Study 4: The Effect of 4 Weeks Motor Imagery Training on Simulated BMX Race Performance

Published in the International Journal of Sport and Exercise Psychology, 2021

6 Study 4: The Effect of 4 Weeks Motor Imagery Training on Simulated BMX Race Performance

6.1 Foreword

This chapter is derived from a published article in the International Journal of Sport and Exercise Psychology, published on December 2020.

Amin Daneshfar, Carl J. Petersen & Daniel E. Gahreman (2021). The effect of 4 weeks motor imagery training on simulated BMX race performance, International Journal of Sport and Exercise Psychology, DOI: 10.1080/1612197X.2020.1869801

Cognitive strategies are well known among athletes in different sporting contexts with MI having been shown beneficial for improving athletic performance. Specifically, there is much evidence showing improvement of muscular strength, power production and motor learning following MI practice. The review of literature in Chapter 2 highlighted that cognitive practice benefits cyclists in both training and competition environments and suggested that the long-term effects of cognitive strategies on BMX riders (e.g. MI) should be investigated further.

Previous chapters (Chapter1, 2, 3) established that improved performance in BMX racing at a sub-elite level is related to riders' anthropometry, strength, power production and aerobic and anaerobic capacity. If MI practice improves muscular strength and power production, BMX riders would benefit by adding this cognitive practice to their training regime. Therefore, following the multidisciplinary approach in this thesis, the purpose of this Chapter was to investigate the effectiveness of applying a 4-week of MI training program in conjunction with riders' routine track training on simulated time trial performance. The results of this study will help BMX coaches and riders understand the potential role of MI practice on BMX racing.

6.2 Abstract

This study investigated the effectiveness of a BMX specific Motor Imagery (MI) program on simulated time trial performance. MI is defined as the visualization of motor activities in the absence of physical movement and has been demonstrated to be effective for a variety of outcomes. However, to date, the transfer of MI has not been adequately evaluated in cycling specific settings. Therefore, using a crossover study, 13 sub-elite BMX riders (11 male, 2 female; age 19.2 ± 3.5 years, height 1.74 ± 0.06 m) undertook four weeks (80 min / week) MI training, in addition to normal BMX training, with a week washout between conditions. Pre and post MI training, track testing included vertical jump and three BMX time-trial time trials.

Our data presented no significant improvement in riders' finish time following MI training in any of the three time trials ($p > .05$), but showed a slight improvement trend. Despite this, relative peak power significantly improved following MI practice compared to the baseline and control conditions ($p < .01$). As a BMX rider's final placing is often decided by a fraction of a second, coaches and practitioners may benefit from including MI in their training program to improve riders' performance. However, more research is required with riders of different competitive levels to test this hypothesis.

KEYWORDS: cognitive strategy, cycling time trial, peak power, imagery ability

6.3 Introduction

Many athletes and sport coaches believe that using cognitive strategies prior to or during skill execution enhances sport performance (Slimani et al., 2016). One method that has been used extensively to improve general motor tasks is Motor Imagery (MI). MI is a form of simulation where the entire physical experience of an action (e.g. feeling, hearing, and seeing) occurs in the mind and has been shown to improve actual performance (Kosslyn et al., 2001). MI is remarkedly similar to the real sensory experience, and shares comparable mechanisms used in the actual movement preparation. MI even stimulates the same brain areas helping to facilitate performance (Kosslyn et al., 2001; Weinberg et al., 2014). As such, MI is a popular method utilised by sport psychologists and has attracted much research attention over the past three decades (Paravlic et al., 2018).

Yue et al. (1992) were the first to provide evidence that MI training could improve muscular strength. They found an increase in strength of 22% compared to ~4 % in the control group and suggested that the central programming of a voluntary contraction may have led to this improvement. Subsequently, evidence of MI benefits for enhancing muscular (the abductor digits, plantar-flexor, and distal/proximal upper extremities) strength (Ranganathan et al., 2004; Smith et al., 2003; Zijdewind et al., 2003), and muscular endurance (Lebon et al., 2010) have also been reported. Furthermore, MI has been shown to have positive effects on absolute and explosive force production, with peak ground reaction forces of an isometric pull being significantly greater when using imagery compared to no imagery (Avila et al., 2015). The above authors explained that imagery may facilitate learning of a new skill by helping the subjects rehearse and become more familiar with the actual movement. More recently, Grospretre et al. (2019) showed short-term MI training significantly improved the plantar flexors' maximal force and rate of force development, as well as resulting in greater spinal and supraspinal adaptations. These authors speculated that the various adaptive changes occurring in the brain, known as neural plasticity, could be the underlying performance-enhancing mechanism. These neural changes include the strengthening of neuronal connections, the addition or removal of connections, and new brain cell formation.

Several imagery theories exist to explain the benefits of imagery. For instance, Jeannerod (1994) argued that imagery and physical practice are functionally equivalent, and both access common neural mechanisms associated with the actual perception, motor control, and emotions of a movement. Alternatively, Lang (1979) introduced the bio-informational theory in which all knowledge is represented in memory as units of information and during that imagery, individuals could access the information stored in long term memory. When required to perform a task in the future, the performer is more likely to recall the correct actions needed to produce the skill from memory. Holmes et al. (2001) combined the bio-informational and functional equivalence theories and created the PETTLEP imagery model. In the PETTLEP model, “P” refers to the athlete’s physical response to the sporting situation, “E” is the environment in which the imagery is performed, “T” is the imagined task, “T” refers to timing (or the pace at which the imagery is performed), “L” is a learning or memory component of imagery, “E” refers to the emotions elicited by the imagery and “P” refers to the visual perspective adopted by the individual. Imagery interventions based on the PETTLEP model have shown to improve complex movement and athletes motor performance in different sports, including field hockey, gymnastics routines, skiing and golf shots (Post et al., 2018). Using the components of the PETTLEP model ensures that imagery is functionally equivalent to physical practice and strengthens stimulus and response associated with the motor task.

Imagery is only beneficial when used by individuals demonstrating sufficient imagery ability (Williams, 2019). Imagery ability is defined as “an individual’s capability of forming vivid, controllable images and retaining them for sufficient time to effect the desired imagery rehearsal" (Morris et al., 2005). Hall (1998) highlighted that everyone has the ability to generate an image, but this may differ in terms of vividness, controllability, kinesthetic feeling, ease, and emotion experience. Thus, imagery ability is multidimensional and can be reflected in a number of ways. In sport, the two main dimensions used to assess imagery ability are ease and vividness (Morris et al., 2005). Alongside choosing the appropriate imagery model, the effectiveness of imagery as a performance-enhancing strategy is dependent on the individual's ability to generate and control vivid images effortlessly. This is supported by Robin et al. (2007) who have demonstrated that following MI practice on tennis service return accuracy, greater improvements were experienced by those who had a better imagery ability.

Researchers recently concluded that cognitive practice benefits cyclists in both training and competition environments. This suggests long-term effects of cognitive strategies (e.g. MI) should be investigated further (Spindler et al., 2018). Cycling research to date has shown that to world-class endurance cyclists, MI appears a useful method of facilitating positive emotional states (Spindler et al., 2019). Additionally, using a mental skills package, including MI, has effectively enhanced Triathlon race performance (Thelwell et al., 2003). Potentially, MI is thought to improve pain management and endurance performance in cycling tasks by decreasing the perception of effort (Razon et al., 2014). Considering the similar effects on the brain of MI training compared to actual physical performance, it is argued that MI training could supplement physical practice and help athletes as a mental and physical preparatory tool (Cumming et al., 2012). Incorporating MI into training schedules could assist cycling coaches in developing riders' optimal performance in various cycling disciplines.

Bicycle Motocross (BMX) is a relatively new cycling discipline, which consists of single-lap sprint races. On a purpose-built dirt race course (~400 meter), eight riders face several jumps, rollers and banked turns requiring multiple physical and technical actions to be enacted. Each race lasts 30-40 s and riders generally have a 15-30 minute recovery between races, dependent upon the level of competition, with up to six races per day (Cowell et al., 2011). Previous research has investigated factors for success in BMX including physiological (muscular power, rate of power production, aerobic and anaerobic fitness level), psychological (audio-visual feedback, state anxiety), biomechanical (start position, gear ratio, cadence) and technical skills (Daneshfar et al., 2020b; Daneshfar et al., 2020d; Debraux et al., 2011b; Rylands et al., 2017c; Zabala et al., 2009b). Notably, factors such as peak power, muscular strength, and jump performance have been highlighted as the key performance indicators in BMX racing (Daneshfar et al., 2020c). In a scoping review Rylands et al. (2019) concluded that more multidimensional studies are required to highlight validated performance characteristics of BMX cycling. They also concluded that correlation of psychological factors with BMX performance needs further investigation. Despite the positive effects of MI training on muscular strength, power, recovery from fatigue and skill improvement shown in recent research (Lebon et al., 2010; Saumur et al., 2018; Slimani et al., 2016), the usefulness of MI practice on BMX performance remains unknown.

In sports such as BMX, specific MI involves multiple muscle groups, open chain movement patterns and motor skills. BMX coaches seeking to obtain performance enhancement, in particular, muscular power and motor skill learning through MI interventions, need research to establish the effects of MI practice on more complex cycling-related tasks. To the best of our knowledge, the only published use of MI with BMX riders tried to simulate their race line positioning. In this study, total power output was found to be higher on the cycle ergometer after focusing on the environmental/emotional context from the external lane using a MI protocol (Di Rienzo et al., 2018). Given the previously highlighted findings showing the potential for MI to improve strength and power tasks, it seems plausible that MI could positively contribute to BMX race performance. Therefore, the purpose of the current study was to investigate the effectiveness of a specific MI training strategy on time trial performance. Based on the previous findings (Lebon et al., 2010; Saumur et al., 2018; Slimani et al., 2016), it is hypothesised that adding MI training to a routine track training program will significantly improve sub-elite BMX riders' time trial times. In addition, it is hypothesised that riders' relative peak power will significantly increase following MI training compared with both baseline and control conditions.

6.4 Methods

6.4.1 Participants

We determined sample size using conservative estimates in the statistical program G*Power 3.1 (Faul et al., 2007) for a within factor repeated measures analysis of variance (ANOVA). A total sample size of 12 riders was required to obtain a moderate effect size (Cohen's $d = 0.50$) using an alpha error probability of 0.05 and statistical power set at 0.80. The target of a moderate effect size was based on previous research exploring MI in cycling performance (Razon et al., 2014). To participate in this study, riders were recruited via advertisement within different BMX clubs and 17 riders expressed their interest. However, only 13 sub-elite BMX riders (11 male, 2 female; age 19.2 ± 3.5 years, height 1.74 ± 0.065 m, training experience 7.5 ± 2.5 years) met all the inclusion criteria and were included in this study. The inclusion criteria was that riders had more than 3 years of BMX experience with regular participation in national competitions, had no current injuries or lack of movement and had no history of cardiovascular disease, hypertension, or diabetes. The study procedures, benefits and potential risks were explained to riders and written consent was obtained. Parental signed consent was secured for those under 18 years. Riders were questioned prior to the intervention regarding their level of exposure to sport psychology and mental skills training. No rider reported having previously received any mental skills education or formal sport psychology support. The researcher provided a general introduction to MI to all riders before testing.

The experiment was conducted according to Helsinki Declaration and approved by the University of Canterbury's Ethics Committee (Ref: HEC 2018/127).

6.4.2 Procedures

Using a randomized, crossover trial design (Figure 6.1), BMX riders were ranked and pair-matched on their baseline test BMX time trial result and randomly allocated to undertake the MI or control condition first. When undertaking the MI condition, riders performed their mental imagery training at home in addition to their routine BMX training. When in the control condition, riders only conducted their normal BMX track training activities and were asked not to perform MI. All BMX specific training was supervised by their coach (3 × 1.5 hour sessions per week) and followed the same intensity during the experiment. Riders trained for four weeks in both training conditions and a one-week no training washout period was employed.

6.4.3 Time Trial Day Testing

Anthropometric and vertical jump. On each test day, rider's body mass (Seca Quadra 808 digital scales, Birmingham, UK) and height (Seca 213 stadiometer, Birmingham, UK) were recorded. Each rider then followed a structured warm-up comprising 5-10 standing-start cycle sprints, and then performed a vertical jump test after five minutes rest (Swift yardstick, Australia). The plastic vanes were adjusted according to the rider's maximum standing reach by extending their arm straight over the head (standing height). The dominant arm was closest to the vanes. Riders then performed three maximal jumps displacing the vanes with their dominant hand. The highest score was recorded.

Power output measurement. Riders then performed three full 342m lap time trials using the same BMX bike (gear ratio of 43/16 fitted with a SRM (Schoberer Rad Messtechnik Fuchsend, Germany) power meter crank. Prior to each test the power meter was configured in combination with SRM instructions. All the relative data including peak power and cadence was downloaded after time trials using Power Control8 software (PC8DeviceAgent). Riders started from the top of a 5m start ramp and a standard electronic start gate was employed.

Heart rate. During the time trial, heart rate (HR) was monitored by the Garmin HR chest strap (HRM-Dual™, USA). A 15-minute passive recovery was undertaken between each time trial.

Time trial time. Time trial time was recorded using two pairs of photocells (NEOtm Swift Performance, Queensland, Australia) positioned at the start gate and on the finish line.

Rate of perceived exertion. Rate of perceived exertion (RPE) was recorded using the 0 – 10 Borg scale ranging from very very light (0) to exhaustion (10) immediately after each time trial (Borg, 1982).

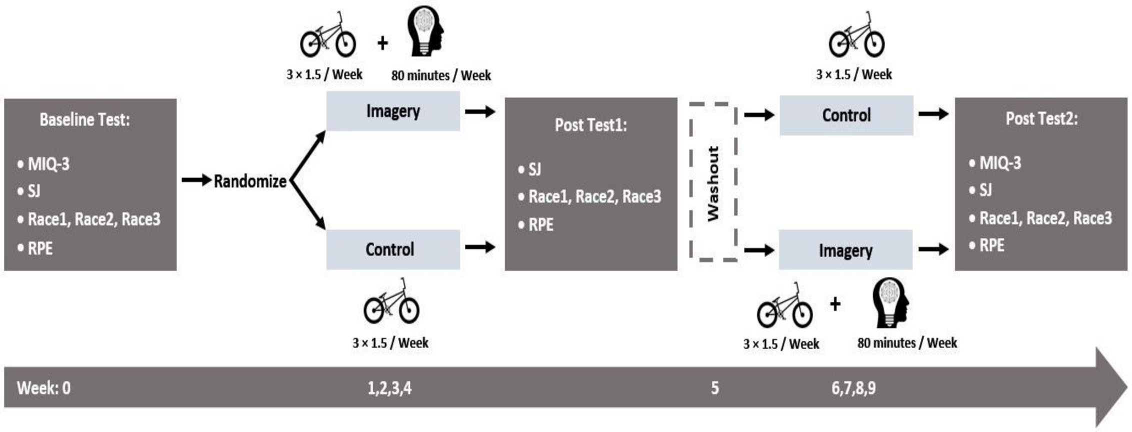


Figure 6.1 Motor Imagery randomised cross over study design.

6.4.4 Motor Imagery

Imagery ability. The Movement Imagery Questionnaire 3 (MIQ-3; (Williams et al., 2012) was used at the baseline and post-test 2 to assess the riders’ ability to image movement external visual imagery (EVI), internal visual imagery (IVI), and kinesthetic imagery (KI). The MIQ-3 is a 12-item questionnaire that assesses the ease or difficulty of generating images of four different movements (i.e., knee lift, jump, arm movement, and waist bend) from an IVI perspective, an EVI perspective, and a KI modality. Participants are required to read a description of each movement, physically perform the movement, and then imagine that movement from the designated perspective. Participants are then required to rate the resultant image on a 7-point Likert scale ranging from 1 (very hard to see/feel) to 7 (very easy to see/feel). After the items for each subscale are averaged, a higher score represents a greater ease of imaging. According to its developers, the MIQ-3 displays good internal consistency (Williams et al., 2012). Current sample demonstrated good internal reliability both at baseline and post intervention with Cronbach’s alpha coefficients above 0.80 (baseline: 0.86, post-test: 0.88).

Imagery training and script. MI training included listening to a ~4-min specific BMX imagery script (2 ×~4 min MI separated by 2 min of relaxation music), which was accessed by a YouTube link (developed by researcher). Riders were asked to practice every second day, twice-a-day for four weeks at home, which totalled 80 min / week. The structure and quantity of the sessions was designed in accordance with elements of a motor imagery training session (position, location, focus, instruction type, order, eyes, perspective, mode) described by Schuster et al.’s for best practice in motor imagery (Schuster et al., 2011).

The script was aligned with the Physical, Environmental, Timing, Task, Learning, Emotion, and Perspective (PETTLEP) model (Anuar et al., 2016; Holmes et al., 2001). To aid in addressing rest of the components of the PETTLEP model, an imagery script was created specifically for the BMX time trial in which the riders were instructed to focus on their personal thoughts and feelings related to a real BMX event. Particularly, the script addressed the task (i.e., strengthening riders' focus on their perception, feelings, and actions as they would during the physical time trial performance), timing (timing of an actual BMX time trial), learning (focusing on the ‘‘feel’’ of the movements as they knew how to ride and were experienced riders), and emotion (experiencing all emotions and arousal associated with performance). The physical nature of the imagery included wearing the same clothing and positioning themselves on the bike as if they were performing the task. While the environmental component ideally involves performing imagery in the physical environment that the task is performed in, logistically this was not possible so a photograph of the track was displayed as the background photo of the YouTube link instead. Riders were instructed to adopt and maintain their preferred visual perspective, either EVI or IVI, whilst also incorporating the different sensations that would be experienced if physically performing the time trial. The script read as follows:

Find a comfortable position: standing, sitting or lying down. You are about to go through the imagery script… Warm up: Imagine a BMX Bike familiar to you. Picture the colour and shape of the bike. You reach for the handle bar, feel the muscles in your hand and forearm flex as they grip the handle, notice the rubber of the handle…

Main Part: Imagine yourself at a race. You enter the track walking with your bike. You take your place under the shield at the start gate, listening to the gear noise and the sounds of the other riders. You notice the race official setting up the gate. Now it is your turn, imagine yourself getting ready for the race, getting into your gear, putting on your gloves and helmet. This is your best race, you are well prepared for and you feel your muscles and body ready for the race…

You get on your bike, you are behind the start gate, and you feel the wind on your face…. other riders are taking position beside you. You sit on your bike, ready for the start order. You remind yourself that you deserve a great performance the [BMX Start Order play]…

GO, GO, GO. Smash out of the gate, you are pedalling hard, the first jump, you are flying …. A smooth landing. Well done. You pump your hands, the first corner … You are pushing yourself, surging forward, digging for every last bit of energy, the last corner, smash through it. One more big push to the finish line, head down and explode across the finish line. You take of your helmet, becoming aware of the feeling of excitement and accomplishment, pride builds inside you, you have succeeded…

Manipulation check. At the end of each MI training session, riders were asked to complete a survey specifying the time and quality of their training from 1 (poor) to 7 (excellent). None of the riders reported missing any of the training sessions. Furthermore, to ensure that riders in the control condition used no imagery training, the YouTube link was removed and a control check was administered. Riders were asked to answer an open-ended question, developed by the authors, describing their daily activities. Data from the control check measure was mainly collected for controlling the experimental condition and was not subjected to statistical analysis.

6.4.5 Data Analyses

All statistical analyses were performed using the SPSS 25 (SPSS, An IBM Company, Amarouk, NY). Data were presented in both mean and 95% Confidence Intervals (CI) and Standard Deviation (SD). A series of 3x3 repeated-measures analysis of variance; for conditions (baseline, MI, control) and time (time trial 1, time trial 2, time trial 3) were used to analyse time trial data. To analyse the vertical jump we used one-way repeated measure

ANOVA. To determine changes in EVI, IVI, and KI imagery ability during the intervention, three separate 2x2 ANOVAs; for conditions (MI, control) and time (baseline, post-intervention) examined any differences between the conditions, or any changes over time. For ANOVAs involving repeated measures, the Mauchly's test of sphericity was used to test the assumptions of homogeneity of variance. When the assumption of homogeneity was violated, the Greenhouse-Geisser values were used to adjust degrees of freedom to increase the critical value of the F ratio. Statistical significance was taken at the level of ($P \leq .05$) except in the instance of a Bonferroni correction in which 0.05 was divided by the number of comparisons. Holm-Bonferroni post-hoc test was also performed to explain significant interactions. Pearson's product-moment correlation coefficient was used to determine the relationship between time trial performance variables and EVI, IVI, and KI imagery ability. Effect sizes were reported as partial eta-squared (η_p^2), whereby values greater than 0.01, 0.06 and 0.14 represented a small, medium and large effect, respectively (Cohen, 1988).

6.5 Results

6.5.1 Imagery Ability

Means and standard deviation of EVI, IVI, and KI on baseline and post-test are presented in Table 1. There was no significant difference of overall imagery ability at the baseline ($p > .05$); however, riders reported significantly greater EVI, IVI and KI post intervention. Results for EVI indicated a significant effect of time, $F(2, 24) = 25.32$, $p = .020$, $\eta_p^2 = 0.55$, but no main effect of condition $F(1.55, 12.13) = 1.89$, $p = .421$, $\eta_p^2 = 0.03$ or interaction of condition and time $F(1.13, 14.12) = 1.21$, $p = .162$, $\eta_p^2 = 0.08$. There was also a significant effect of time for IVI and KI (IVI: $F(2, 24) = 23.15$, $p = .001$, $\eta_p^2 = 0.65$; KI: $F(2, 24) = 27.22$, $p = .001$, $\eta_p^2 =$

0.71). While the results showed no significant effect of condition (IVI: $F(1.57, 10.32) = 18.25$, $p = .251$, $\eta_p^2 = 0.08$; KI: $F(1.45, 12.11) = 21.08$, $p = .231$, $\eta_p^2 = 0.09$) or interaction of condition and time (IVI: $F(1.21, 11.02) = 19.15$, $p = .525$, $\eta_p^2 = 0.11$; KI: $F(1.25, 10.18) = 25.03$, $p = .141$, $\eta_p^2 = 0.06$) for IVI and KI. Post hoc analysis revealed that both the MI and control conditions improved their EVI (MI: p = .003; control: p = .011), IVI (MI: p = .002; control: p = .013) and KI (MI: p = .005; control: p = .001) imagery ability from before to after the intervention.

Furthermore, our results found no significant correlation between MIQ-3 subscales and time trial finish time (EVI: $r = 0.26$; $p = 0.92$, IVI: $r = 0.32$; $p = 0.57$, KI: $r = 0.28$; $p = 0.21$) or relative peak power (EVI: $r = 0.16$; $p = 0.24$, IVI: $r = 0.32$; $p = 0.24$, KI: $r = 0.18$; $p = 0.41$).

During the training weeks, the self-estimated imagery survey (mean: 5.8 ± 1.3 out of 7) did not show any significant fluctuation from one day to another $F(2.12, 25.11) = 1.25$, $p = .345$, $\eta_p^2 = 0.09$.

6.5.2 Time Trial Finish Time

The results showed no statistically significant interaction of condition and time for the time trial time $F(2.17, 26.10) = 1.38$, $p = .267$, $\eta_p^2 = 0.10$. Despite that, there was an improvement trend of 2.4%, 0.6%, and 0.8% in MI condition compared to baseline for time trial 1, time trial 2 and time trial 3, respectively.

There was no statistically significant condition effect $F(1.40, 16.74) = 0.82$, $p = .451$, $\eta_p^2 = 0.06$ or time effect $F(2, 24) = 1.41$, $p = .263$, $\eta_p^2 = 0.10$ on time to finish (Table 2).

6.5.3 Relative Peak Power

As presented in (Table 2), there was a significant condition effect $F(2, 24) = 25.59$, $p = .001$, $\eta_p^2 = 0.68$ of MI which resulted in a significant increase in relative peak power when compared to baseline and control condition ($p < .001$). Furthermore, there was a significant time effect on relative peak power where the values in time trial 1 were significantly greater than time trial 2 $F(2, 24) = 3.58$, $p = .004$, $\eta_p^2 = 0.23$. However, the interaction of condition and time was not significant for relative peak power $F(2.53, 30.40) = 1.52$, $p = .230$, $\eta_p^2 = 0.11$. The results of cadence at peak power failed to present any statistically significant difference of time and condition $F(1.43, 12.25) = 2.12$, $p = .344$, $\eta_p^2 = 0.12$ and $F(2.52, 20.28) = 5.52$, $p = .144$, $\eta_p^2 = 0.22$, respectively.

6.5.4 Vertical Jump, Heart Rate, and RPE

There were no statistically significant effect of condition $F(2, 24) = 0.79$, $p = .467$, $\eta_p^2 = 0.06$ or time $F(2, 24) = 0.32$, $p = .162$, $\eta_p^2 = 0.10$ for vertical jump. In addition, current results for HR and RPE showed no statistically significant effect of time (HR: $F(2, 24) = 21.25$, $p = .141$, $\eta_p^2 = 0.05$; RPE: $F(2, 24) = 20.12$, $p = .321$, $\eta_p^2 = 0.02$), or condition (HR: $F(2, 24) = 25.11$, $p = .091$, $\eta_p^2 = 0.21$; RPE: $F(2, 24) = 19.12$, $p = .241$, $\eta_p^2 = 0.11$) (Table 3).

Table 6.1 Mean ± SD of Movement Imagery Questionnaire-3 scores.

	Baseline	MI	Control
MIQ-3 sub-scales			
EVI	4.23 ± 1.21	4.85 ± 0.98 *	4.65 ± 1.03 *
IVI	4.37 ± 1.35	4.78 ± 0.92 *	4.70 ± 0.95 *
KIN	4.22 ± 1.26	4.60 ± 1.10 *	4.51 ± 0.99 *

EVI: external visual imagery, IVI: internal visual imagery, and KI: kinesthetic imagery

* Significantly greater than Baseline ($p < .01$)

Table 6.2 Mean ± SD of time trial time and power output.

	Baseline	MI	Control
Time Trial Finish Time (s)			
time trial 1	36.00 ± 1.34	35.15 ± 1.44	36.13 ± 1.33
time trial 2	36.22 ± 1.67	36.02 ± 1.57	36.05 ± 1.55
time trial 3	36.34 ± 1.56	36.04 ± 1.30	36.51 ± 1.55
Peak Power (W)			
time trial 1	1271 ± 148	1312 ± 145	1277 ± 143
time trial 2	1305 ± 179	1215 ± 199 *	1290 ± 175
time trial 3	1265 ± 169	1280 ± 152	1246 ± 166
Relative Peak Power ($W \cdot kg^{-1}$)			
time trial 1	18.1 ± 2.1	18.8 ± 2.3 †	18.2 ± 2.1
time trial 2	18.6 ± 2.4	18.5 ± 5.7 *	18.4 ± 2.3
time trial 3	18.0 ± 2.5	18.3 ± 2.2	17.8 ± 2.4

† Significant difference ($p < .01$) between MI and both Baseline and Control conditions

* Significant difference ($p < .01$) between time trial 1 and time trial 2

Table 6.3 Time trial data mean with 95% CI.

	time trial 1	time trial 2	time trial 3	Average
Cadence at Peak power ($rev \cdot min^{-1}$)				
Baseline	137 [131.2-143.2]	130 [124.3-136.0]	135 [129.7-141.3]	134 [130.8-137.7]
MI	136 [130.8-141.5]	132 [126.6-134.4]	134 [130.2-138.5]	134 [132.3-136.4]
Control	137 [131.8-142.5]	132 [127.9-135.9]	136 [132.8-140.3]	135 [132.3-138.2]
Heart Rate ($beats \cdot min^{-1}$)				
Baseline	174 [168-181]	182 [178-186]	181 [177-186]	179 [175-182]
MI	179 [176-183]	183 [181-186]	183 [180-186]	182 [180-183]
Control	176 [173-182]	183 [180-186]	181 [176-185]	180 [176-183]
RPE (0-10)				
Baseline	8.5 [7.4-9.3]	8.6 [7.5-9.7]	8.5 [7.4-9.5]	8.2 [8.3-9.6]
MI	8.8 [7.7-9.8]	9.4 [8.3-9.6]	9.7 [8.5-10.0]	9.3 [8.3-9.7]
Control	8.6 [7.2-9.7]	9.5 [8.3-10.0]	9.5 [8.2-10.0]	9.4 [8.4-9.7]
Vertical Jump (cm)				
Baseline	48.5 [42.3-52.8]			
MI	50.2 [44.7-53.0]			
Control	50.8 [44.8-53.9]			
Mass (kg)				
Baseline	70.4 [67.1-73.7]			
MI	69.8 [66.6-73.0]			
Control	70.3 [67.1-73.5]			

6.6 Discussion

The aim of this study was to assess whether using a BMX specific MI training would improve riders' performance. In particular, the effectiveness of MI on power measures and time trial performance was investigated. The main finding of our study revealed that four weeks of MI training did not significantly improve riders' time trial time, yet we did find a significant improvement in riders' power production within the first and third time trials. There was no significant difference in riders' imagery ability at baseline and their ability improved equally across conditions. While many studies have investigated the efficacy of MI as a cognitive strategy, to our knowledge, this is the first study to use MI practice alongside routine track training in BMX riders. To simplify the practical applicability of the current study and descriptive utility, we have included both effect sizes and confidence intervals. Despite the importance of statistical significance, in studies with a small sample size, consideration of the magnitude of effect is often more sensible for the interpretation of the results (Rhea, 2004).

MI practice has been used as a substitute or supplementary training program to preserve muscle function when athletes are not being exposed to maximal training intensities such as recovering from injury (Paravlic et al., 2018). In addition, Cumming et al. (2002) suggested that imagery can be considered deliberate practice where highly structured and purposeful practice is applied to improve performance. As indicated in Table 2, time trial times did not improve statistically following MI practice across three time trials. Despite this, there appears to be a trend of faster time trial times for riders in the MI condition. In the first time trial, riders finished the time trial 2.4% and 4% faster than the baseline and control conditions, respectively. In a BMX race, competition is generally very close and any minor improvement in finish time, relative to other competing riders, can significantly affect final placing. Therefore, BMX coaches and researchers are always trying to find ways to improve the race time and general performance. For instance, Rylands et al. (2017c) ascertained that optimal cadence selection could result in a 1.0 s faster time to power production. Similar to the current study, their results were not statistically significant but the authors concluded (based on a publicly accessible database during the 2012 World Cup Supercross Series) that these improvements could affect a riders' final placing between 1st and 4th position. In our study, four weeks of MI training, in addition to routine BMX training, improved riders' average time by 1.44 s, which was not statistically significant. However, this change may have a real influence on riders' final ranking.

The second main finding of our study was a large ~4% improvement in relative peak power in the first time trial compared to the baseline and control conditions. Riders in MI condition also reached ~3% more relative peak power in time trial 1 compared to time trial 2. In the current study, producing higher power following MI training was similar to previous research that showed MI can improve strength and power. For instance, Saumur et al. (2018) indicated that three weeks of MI training may have the potential to improve quadriceps strength by 10%. Ranganathan et al. (2004) demonstrated a 35% increase in elbow flexion strength after MI in young healthy individuals. Similar findings have also been reported by Lebon et al. (2010) who identified a 26% increase in the maximal concentric strength and eight additional repetitions for the leg press after MI training. Yue et al. (1992) have also reported that MI may significantly increase muscle twitch force. There are possible explanations for why current MI interventions theoretically could provide an effective tool for BMX coaches and riders.

Firstly, it is supported that neurological adaptation after mental practice are similar to those elicited by physical practice (Paludo et al., 2017). This can be obtained with a short period of MI training, which might improve coordination and enhance muscle fibre recruitment. Secondly, cognitive components of the MI script, which refer to the imagery of time trial strategies, could lead to higher confidence and decreased anxiety levels (Lebon et al., 2010; Slimani et al., 2016). Therefore, MI might have contributed to improve peak power by enhancing riders' motivation and self-confidence, or regulating anxiety related to competition. Future research can assess the effectiveness of MI training on motivation and anxiety level and validate this among BMX riders. Finally, the PETTLEP model utilised in designing the imagery script, maximized the functional equivalence by ensuring that the imagery performed was a close representation of actual BMX time trial performance. This is in line with previous reports showing the PETTLEP-style imagery is effective to improve muscular strength (Smith et al., 2003; Wakefield et al., 2011; Wright et al., 2009) and sport performance (Smith et al., 2007; Wakefield et al., 2009). The largest MI performance effects are seen when MI is completed frequently (Wakefield et al., 2011). Riders in the current study were practicing MI twice a day/ three times a week. Thus, this design was considered deliberate imagery practice

(Cumming et al., 2002), and other findings also showed that a greater frequency of imagery produced greater improvement in performance (Wakefield et al., 2009; Wakefield et al., 2011).

It is worth noting that we did not identify any changes in vertical jump performance, which was used to monitor potential changes in riders' muscular power after using an MI protocol. Our results supported the specificity of race MI script, as BMX riders were using MI to simulate time trial performance and not vertical jump. Our data also showed no significant effect of MI training on riders' HR and RPE which were considered as control variables to monitor riders' physiological response during the race. Presenting similar HR and RPE levels across conditions provides evidence that all riders experienced similar physical load during effort expenditure. While Razon et al. (2014), reported that using MI could assist endurance cycling task by decreasing RPE, our data supported those studies that failed to identify any differences in RPE during physical performance (Connolly et al., 2003; Razon et al., 2010).

In the current study, imagery ability improved equally across conditions. This supports previous findings that MI practice can improve imagery ability (Cumming et al., 2001; Williams et al., 2013a). As having a better imagery ability can significantly influence the MI effects, we measured this variable pre and post intervention. Our results found no association between improved imagery ability with riders' time trial performance. This might be due to the method (self-reported questionnaire) being used to measure imagery ability, instead of using a combination of qualitative, psychometric, chronometric, and psychophysiological approaches (Collet et al., 2011).

In contrast to current findings, Vergeer et al. (2006) found a positive correlation between imagery vividness, measured throughout the intervention, and improvement in movement flexibility. Williams et al. (2013a) showed improving imagery ability resulted in an enhancement in motor performance of a golf putting task. Following MI practice, individuals with lower imagery ability can experience improvements in being able to see images in two days and being able to feel the images in three days. Riders in the current study had no previous experience of MI training and demonstrated no differences in baseline imagery ability.

This was the first study to determine the effects of MI on BMX time trial performance. Our results were somewhat conflicting, as there were improvements in power production, but the trend of improved time trial times did not reach the threshold for statistical significance. While power is believed to be a key performance indicator in a BMX time trial, there are apparently other factors influencing riders' finish time. For instance, in a BMX race and especially in the third and fourth straightway, technical skill and riding coordination can significantly affect performance (Cowell et al., 2011; Cowell et al., 2012a; Philippe Campillo, 2007). However, in the current study, we did not measure riders' skill execution; it is possible that the improved power production coincided with a decrease in skill execution, thereby offering an explanation for the lack of significant improvement in race time. Skill execution is therefore an important area for future research to consider when assessing the effect of MI training on BMX riders' skill development.

As MI did not decrease performance, it is likely to be a safe addition to BMX training programmes and a supplement to normal training. Emphatically, as MI can be a genuine learning approach (Cumming et al., 2012; Paravlic et al., 2018), coaches can use MI training as an alternative tool for teaching new techniques or while training young riders. Elite riders may respond differently to the current study and further research should be undertaken to ascertain if MI can improve time trial performance when combined with physical training. Future research should also aim to identify the effectiveness of MI intervention for improving movement technique across a range of skill types for both elite and sub-elite riders. Finally, research should explore the optimal method for delivering MI intervention, for example, using different scripts or establishing the effect of imagery on a particular part of the BMX time trial such as the start or technical sections.

It is important to point out several possible limitations associated with the experiment. Firstly, the 2 × ~4min MI practice applied in the current study might have been too long as riders had no previous experience with imagery and this could potentially have affected the quality of the imagery sessions. Furthermore, as there are no agreed evidence-based guidance for dose-response of imagery interventions, further research is required to validate the optimal length of MI script. In addition, 45% of the current script was race preparatory phase, which is similar to sport imagery, and 55% was the main race section of motor imagery. Future work must consider investigating the optimal combination of sport imagery and motor imagery when developing the script. The content of the current script was fixed and not personalized in any way during the training. We assumed that consistency of the MI might help riders to familiarize better with the script. Furthermore, we only apply a one-week washout period in the crossover design due to the riders' availability and annual competition schedule. Future research may look at applying more personalized scripts, as well as a longer washout period to avoid any carry-over effect of MI training. In addition, as individuals may experience different physiological responses to MI training and riders in the current study practiced MI at home, so it was hard to monitor their physiological characteristics during or after training. Future studies, may consider supervising training and monitoring HR, or electromyography to determine the muscular response to the MI training and compare these with the physical training in the BMX race. Another limitation of the current study was that the manipulation check did not provide insight regarding imagery quality in detail (e.g., visual perspective, ease of generating, vividness, controllability). Reporting the quality of MI sessions was perhaps too broad to understand the riders' experiences throughout the intervention. Hence, to understand the individual experiences of the riders during MI training, a more precise measurement of imagery quality is required (Williams et al., 2013b). The environmental component ideally involves performing imagery in the physical environment that the task is actually performed in; logistically this was not possible so a photograph of the track was used instead. It is proposed that more vivid imagery may occur when an individual holds a relevant piece of sporting equipment (Anuar et al., 2016), however we did not ask riders to sit on their bike while imagining. Therefore, the script was not entirely consistent with the PETTLEP model. Future studies should apply MI training while entirely following PETTLEP model (Wakefield et al., 2013) and consider practicing at the BMX track prior to each race or on separate days. Finally, the small sample size potentially affected the current study outcomes. In the current study, we applied MI training among 13 sub-elite BMX riders. Elite riders with a higher technical and physiological level may respond differently to the MI training. Future research should recruit more riders and consider using elite level riders to validate our findings.

6.7 Conclusion

In conclusion, this study provides initial evidence that combining 4 weeks of MI training program with BMX practice does not significantly affect riders' time trial time, but could improve peak power production. Improved muscular power in the current study following MI training supported the application of MI as a supplementary training method beside physical practice to enhance athletic performance. Particularly, this information might be of interest to BMX coaches and riders themselves, who would like to add mental practice in their annual training program. Athletes should also be encouraged to incorporate the PETTELEP model into their imagery as much as possible to achieve more effective results. In addition, imagery ability improved across both conditions in all three sub-scales (EVI, IVI, KI), however, current results failed to show any significant correlation between imagery ability and riders' time trial time and relative power. Future research might look to explore the effect of MI training and use alternative measures to understand the role of this cognitive strategy in sport performance.

Chapter 7

Study 5: Caffeinated Chewing Gum Improves Simulated BMX Race Performance

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7 Study 5: Caffeinated Chewing Gum Improves Simulated BMX Race Performance

7.1 Foreword

This chapter is derived from a published article in International Journal of Sport Nutrition and Exercise Metabolism in 2020.

Daneshfar, A., Petersen, C. J., Koozehchian, M. S., & Gahreman, D. E. (2020). Caffeinated Chewing Gum Improves Bicycle Motocross Time-Trial Performance, International Journal of Sport Nutrition and Exercise Metabolism, 30(6), 427-434. DOI: https://doi.org/10.1123/ijsnem.2020-0126

The previous chapter (Chapter 6) showed that using cognitive training along with routine BMX practice could improve riders' power production in a simulated race condition, but unfortunately, this did not improve race time. Along with using psychological approaches, athletes routinely use nutritional interventions to improve performance. Consuming caffeine pre and/or during competition in many sports has been shown to be ergogenic for endurance performance. More recent evidence hints that anaerobic performance could also benefit from caffeine consumption.

Currently, there is no scientific evidence regarding caffeine's ergogenic effects on BMX racing performance. If caffeine enhances short-duration, high-intensity performance by increasing anaerobic power and sprint speed (Hahn et al., 2018), then BMX riders may benefit from its consumption. Therefore, the purpose of this chapter was to investigate whether consuming a low dosage of caffeine via chewing gum 10 min prior to a BMX time trial could enhance cycling performance. These findings would be of immediate interest to BMX riders who are currently unsure of the effects of caffeine on racing performance.

7.2 Abstract

This study aimed to identify the acute effects of caffeinated chewing gum (CAF) on BMX time trial (TT) performance. In a randomized, placebo-controlled, double blind crossover design, 14 male BMX riders (age: 20.0 ± 3.3 years; height: 1.78 ± 0.04 m; body mass: 72 ± 4 kg), consumed either (300mg; 4.2 ± 0.2 $mg \cdot kg^{-1}$) caffeinated (300mg caffeine, 6g sugars) or a placebo (0 mg caffeine, 0g sugars) gum, and undertook three BMX TTs. Repeated measure analysis revealed that CAF had a large ergogenic effect on TT time $F(1, 14) = 33.570$, $p = .001$, $\eta_p^2 = 0.71$; -1.5% ± 0.4 compared to the placebo. Peak power and maximal power-to-weight ratio also increased significantly compared to the placebo condition [$F(1, 14) = 54.666$, $p = .001$, $\eta_p^2 = 0.79$; +3.5% ± 0.6], and [$F(1, 14) = 57.399$, $p = .001$, $\eta_p^2 = 0.80$; +3% ± 0.3], respectively. Rating of perceived exertion (RPE) was significantly lower $F(1, 14) = 25.020$, $p = .001$, $\eta_p^2 = 0.64$ in CAF (6.6 ± 1.3) compared to the placebo (7.2 ± 1.7). Administering a moderate dose (300mg) of CAF could improve TT time by enhancing power and reducing perception of exertion. BMX coaches and riders may consider consuming CAF before a BMX race to improve performance and reduce RPE.

Keywords: caffeine, time trial, power output, RPE

7.3 Introduction

Research demonstrates anaerobic performance can improve following caffeine supplementation (Stojanović et al., 2019). Proposed mechanisms include increasing neurotransmitter release and motor unit firing rates (Kalmar, 2005), enhancing muscle contractility as a result of altered calcium kinetics and/or sensitivity (Allen et al., 1995), and decreasing perception of effort related to adenosine receptor antagonism (Davis et al., 2003). A recent meta-analysis demonstrated caffeine might induce meaningful improvements in power and upper body muscular strength (Grgic et al., 2018). Acute improvement in vertical jump height following a single caffeine ingestion has reported roughly equivalent to 4 weeks of plyometric training (Grgic et al., 2018; Markovic, 2007). However, other studies have reported no improvements in anaerobic performance following caffeine consumption (Anderson et al., 2018a; Polito et al., 2016). Given various methodological considerations including dose, consumption method (capsules/pills, drink, chewing gum) and testing procedures (Goods et al., 2017), the effects of caffeine on short-duration high-intensity performance are equivocal.

Chewing gum is an alternate form of caffeine administration and was first used by military to rapidly restore alertness and performance (Wickham et al., 2018). Effective absorption of caffeine via gum occurs primarily through buccal mucosa within 5-10 min of administration, compared to 20-30 min with capsule ingestion, although total caffeine absorption over time is not different (Syed et al., 2005; Wickham et al., 2018). Previous studies have used caffeine doses ranging from 100-300mg, administered 5-10 min pre exercise. Venier et al. (2019) reported up to 4.5% improvement in vertical jump and power in resistance-trained men after consuming 300mg caffeinated chewing gum (CAF). Paton et al. (2010) administered 240mg of CAF to competitive cyclists who completed four sets of five 30-second maximal sprints with 30 s of active recovery between each set. Their results showed that the rate of dropped power output in sets 3 and 4 was significantly reduced after CAF versus placebo.

Similarly, Ryan et al. (2013) observed enhanced cycling time trial after delivering 300 mg of caffeine via chewing gum 5 min before exercise. Interestingly, the same dosage 60 and 120 min pre-exercise failed to show any ergogenic effects. Therefore chewing CAF may prove beneficial where athletes are required to provide a quick increase in repeated anaerobic performance, such as in Bicycle Motocross (BMX) racing.

BMX racing is a mass-start bicycle event where riders race entirely in a standing position. A race typically lasts 35–45 s and takes place on a 300–400m track. Riders generally complete six races on a competition day with 15-30 min recovery between races (Cowell et al., 2012b). Multiple physiological factors contribute to the success of a rider including explosive start, time to peak power, and anaerobic muscular power (Daneshfar et al., 2020d; Debraux et al., 2011a). BMX is considered an intermittent sprint cycling sport and researchers continue to investigate ways to improve performance (Daneshfar et al., 2020b; Rylands et al., 2019).

If caffeine enhances short-duration, high-intensity performance by increasing anaerobic power and sprint speed, then BMX riders may benefit from the consumption of CAF. No previous study has investigated the benefits of caffeine administration on BMX performance. This study aimed to determine the acute effects of CAF on BMX TT performance. It was hypothesised that CAF would improve TT time and power production.

7.4 Methods

7.4.1 Experimental Design

In a randomized, placebo-controlled, double blind, crossover design, the effects of consuming CAF was assessed on TT time as the primary outcome. Power output, blood lactate (BL), heart rate (HR) and RPE were also measured as possible mechanistic factors responsible for changes in TT time. After familiarisation, data were collected on two additional occasions (CAF trial, placebo trial), interspersed with one-week wash-out periods. This study was conducted during the competitive phase of the BMX season, and all trials took place between 5-7pm to control for diurnal variation (Figure 7.1). The study was carried out according to the Declaration of Helsinki and approved by the University of Canterbury's Ethics Committee.

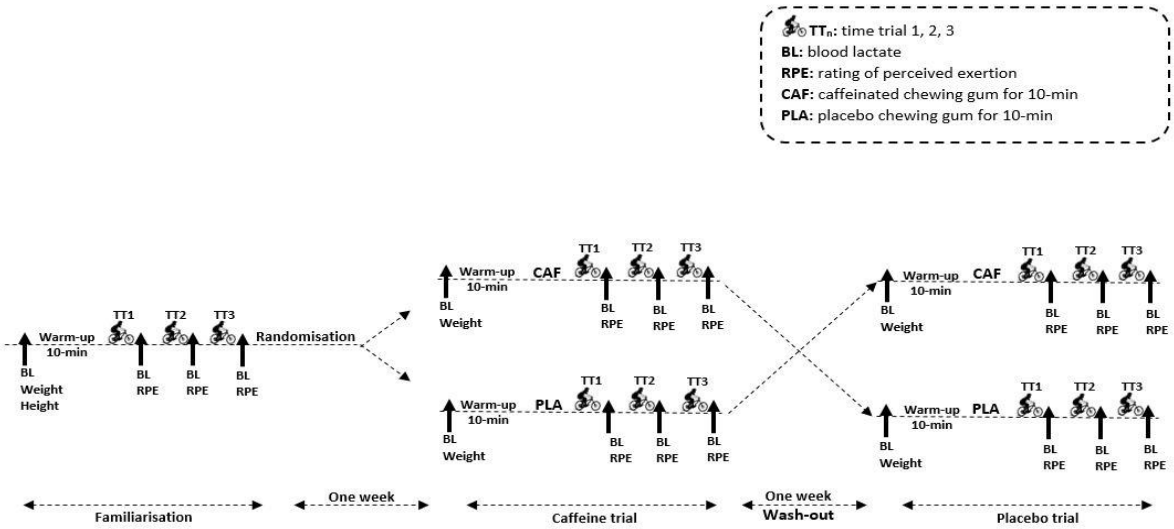

Figure 7.1. Overview of the experimental design, T_n: time trial 1, 2, 3, BL: blood lactate, RPE: rating of perceived exertion, CAF: caffeinated chewing gum, PLA: placebo chewing gum.

7.4.2 Participants

Riders for the study were recruited via advertisement within BMX clubs, and 16 riders expressed interest. Only 14 male riders, who compete regionally and train 4 sessions/week, (age: 20 ± 3.3 years; height: 1.78 ± 0.04 m; body mass: 72 ± 4 kg; BMX experience: 6.5 ± 2 years) met all the inclusion criteria and were included in the study. Riders needed to be 16-35 years, not a regular caffeine consumer, or have any allergies to caffeine and have no current injuries or movement restrictions. All riders were informed of the purpose and risks associated with participation before giving their written consent. Parental consent was obtained for riders under 18-years of age. To calculate study power, a conservative estimate in the statistical program G*Power 3.1 (Faul et al., 2007) for a within factor repeated measures analysis of variance (ANOVA) was performed. This analysis suggested a minimum of 12 riders to obtain a moderate effect size (Cohen's $d = 0.50$) based on research examining effects of CAF on sprint cycling (Paton et al., 2010), an alpha error probability of 0.05, and statistical power of 0.90.

7.4.3 Dietary and Food Control

To identify any caffeinated products that riders regularly consumed, they were provided with a list of common caffeinated products including beverages, food, medicines and supplements prior to participating in the study. A 3-day food diary analysis showed average daily caffeine consumption was ~52.8 ± 40.0mg, which is classified as low caffeine users (Paton et al., 2010). Riders were instructed to follow an identical diet, abstain from caffeine and any vigorous physical activity 24-hours prior to the familiarisation trial, and replicate for subsequent trials.

7.4.4 Experimental Trial

Riders first performed a familiarisation trial, followed by two additional trials separated by a one-week wash-out period. In the familiarisation trial, height and mass were measured, then, after a 10-min standard warm-up, riders performed three BMX TTs interspersed with 15 min passive recovery. TTs were conducted on a 342m outdoor BMX track with a 28° descent, 5m high start ramp, four straights with several technical jumps on each straight section, and three corners. On completion of the familiarisation trial, an independent academic, who was not an investigator in this study, randomized the order in which riders would complete two other trials, using a random sequence generator (Graphpad Software Inc. California, USA). On the two additional trials, riders' weight was measured and they completed similar BMX TTs with either CAF or a placebo administered. The TTs were conducted in summer at temperatures of 19-25 ºC, humidity of 40-45%, and wind speed of ~5-8 km/hr ("Metservice ", 2020).

7.4.5 CAF Administration

Caffeine was administered as an absolute dose of three pieces (300mg; 4.2 ± 0.2 mg·kg^{-1} body mass) of a commercially available gum (Military Energy Gum, Chicago, IL); with each stick providing 100mg of caffeine and 2 g of sugars. The placebo was a similar looking and tasting (0 mg caffeine, 0 g sugars), commercially available gum (Spearmint Extra, NSW, AU). In order to aid blind delivery, gums were divided into small pieces and placed in a container. The effectiveness of blinding was explored following the method by Saunders et al. (2017). In this study, we asked the riders before and after each TT which type of gum they had consumed. The 3-scale response included: (1) caffeinated gum, (2) placebo gum, and (3) I do not know. In both experimental conditions (caffeine and placebo) the gums were chewed for 10 min before TTs (Venier et al., 2019), then expectorated into a container.

7.4.6 Performance Measures

The performance measures (dependent variables) included TT time, absolute peak power, maximal power-to-weight ratio (MPW), time to peak power, cadence at peak power, BL, HR, and post-TTRPE. To record TT time, two pairs of photocells (NEOtm Swift Performance, Queensland, Australia) were positioned at the start gate and on the finish line. BL concentration (mmol·L^{-1}) was measured using a Lactate Pro2 analyzer (Arkray, Kyoto, Japan). A finger prick was taken before warm up and three minutes post each TT (Tanner et al., 2010). To record RPE, riders rated "how hard was that TT" on a CR-10 Borg scale immediately following each TT. The RPE represented a recall of their feeling during the TT that they had just completed (Borg, 1982; Foster et al., 2001). This method was introduced to riders in the familiarisation trial and was replicated for the additional trials. A Garmin HR chest strap (HRM-Dual™, USA) was used to monitor HR during TTs.

Power output was measured using an SRM (Schoberer Rad Messetechnik) power meter, which incorporates an eight strain gauge and 175mm crank arm. This was attached to the BMX testing bike (gear ratio of 43/16) used by all riders. SRM has shown to be a valid tool for measuring power output during field conditions (Gardner et al., 2004). All the relative power output data were downloaded using Power Control8 software (PC8DeviceAgent). Relative maximal power to riders' weight was also calculated and presented as MPW ($W \cdot kg^{-1}$).

7.4.7 Statistical Analysis

Statistical analyses were performed using SPSS 25 (SPSS, An IBM Company, Amarouk, NY). Data are presented as mean ± standard deviation (SD) and an alpha level of $p \leq .05$ was considered statistically significant. A series of 2x3 repeated-measures analysis of variance for conditions (CAF, placebo) and time (TT1, TT2, TT3) were used to analyse data. With repeated measures, when ANOVA interactions were significant, adjusted Bonferroni post hoc tests were also performed. Effect sizes were reported as partial eta-squared (η_p^2), with values of <0.10, 0.10–0.24, 0.25–0.39 and ≥ 0.40 considered trivial, small, moderate, and large effect sizes, respectively (Cohen, 1992). A coefficient of variation was calculated using data collected during familiarisation TTs and placebo TTs to study the day-to-day variation of the performance variables. To explore the effectiveness of blinding, the Bang Blinding Index (BBI) was utilized. The blinding index was scaled to an interval of -1 to 1, with 1 indicating complete lack of blinding, 0 being consistent with perfect blinding and -1 indicating opposite guessing. Blinding data was reported as a percentage of individuals who identified the correct condition beyond chance.

7.5 Results

7.5.1 Body Mass

There was no significant difference in riders' body mass $F(2, 28) = 3.452$, $p = .451$, $\eta_p^2 = 0.19$ in CAF trial (72.4 ± 3.0 kg) compared to placebo trial (72.2 ± 6.2 kg).

7.5.2 Time Trial Time

There was a significant condition effect on TT time $F(1, 14) = 33.570$, $p = .001$, $\eta_p^2 = 0.71$; -1.5% ± 0.4 following CAF consumption compared to placebo. There was no significant interaction of condition × time $F(1.65, 23.16) = 0.105$, $p = .866$, $\eta_p^2 = 0.01$ on TT time (Figure 7.2)

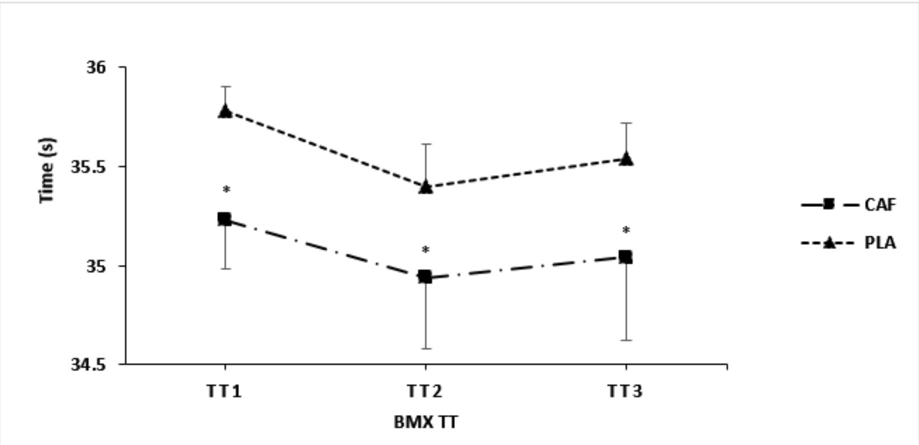

Figure 7.2 Mean ± SD of the BMX performance time over three time trials; CAF: caffeinated chewing gum, PLA: placebo, TT: time trial.

***** Significant main effect of condition $p < .001$, indicating that riders completed each TT faster following CAF compared to PLA.

7.5.3 Power Output

Peak power. A significant condition effect was observed for peak power $F(1, 14) = 54.666$, $p = .001$, $\eta_p^2 = 0.79$ and riders in the CAF condition generated more power compared to placebo +3.5% ± 0.6.

There was no significant interaction of condition × time $F(2, 28) = 3.420$, $p = .082$, $\eta_p^2 = 0.14$ on riders' peak power.

Maximal power-to-weight ratio. Consuming CAF influenced riders' MPW $F(1, 14) = 57.399$, $p = .001$, $\eta_p^2 = 0.80$ with values in the CAF condition being 3% ± 0.3 greater than placebo (Figure 7.3). There was no significant interaction of condition × time $F(2, 28) = 3.512$, $p = .088$, $\eta_p^2 = 0.13$ on riders' MPW.

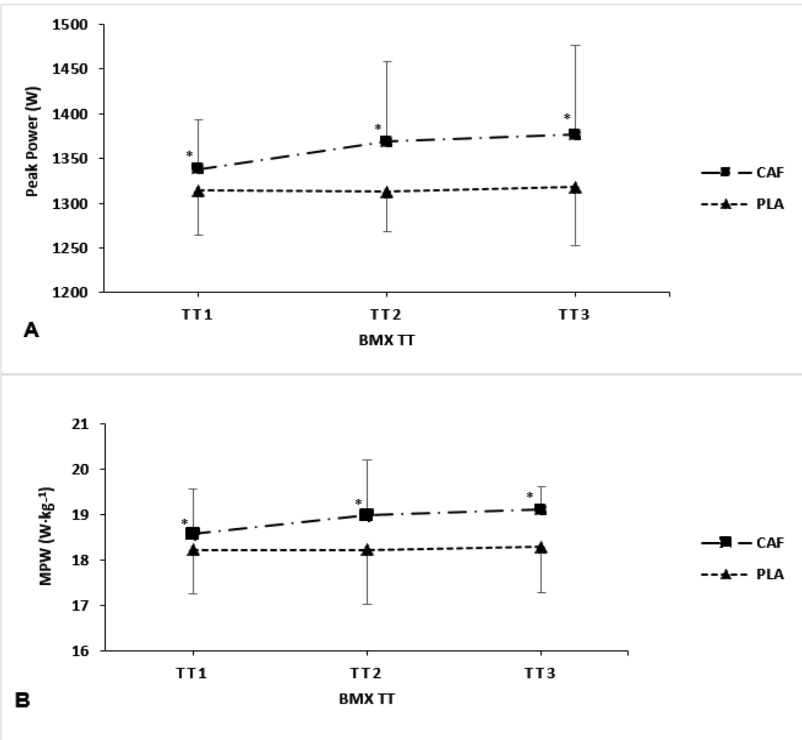

Figure 7.3 Mean ± SD of A: peak power, B: MPW: maximal power-to-weight ratio over three time trials; CAF: caffeinated chewing gum, PLA: placebo, TT: time trial.

* Significant main effect of condition $p < .001$, CAF more than PLA.

Time to peak power. There was no significant interaction of condition × time $F(2, 28) = 0.621$, $p = .411$, $\eta_p^2 = 0.10$, nor condition effect $F(1, 14) = 1.890$, $p = .124$, $\eta_p^2 = 0.14$ on riders time to peak power (Figure 7.3).

Cadence. Our data demonstrated no significant main effect of condition $F(1, 14) = 2.542$, $p = .133$, $\eta_p^2 = 0.15$ on cadence at peak power. There was no significant interaction of condition × time $F(2, 28) = 3.310$, $p = .098$, $\eta_p^2 = 0.19$ on riders' cadence.

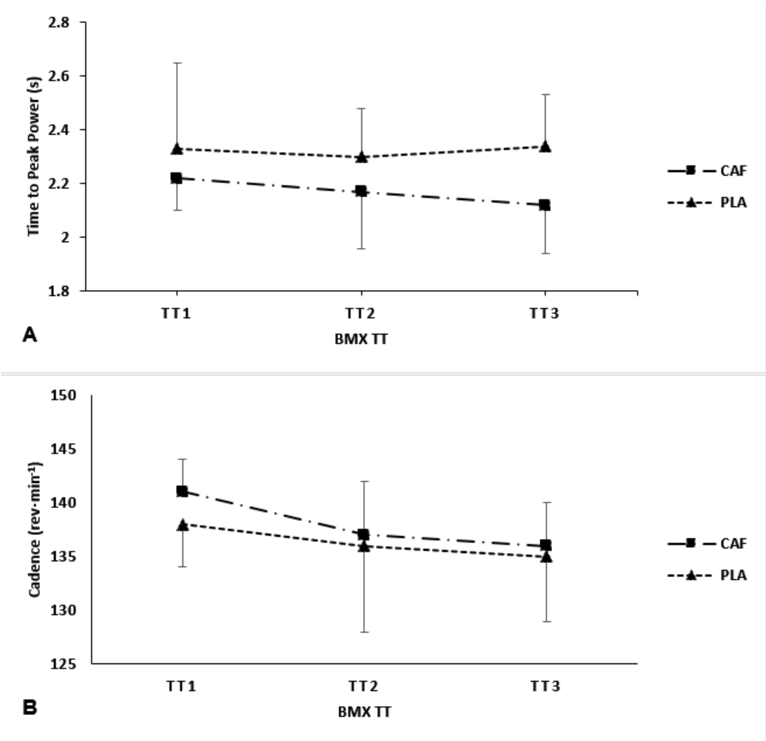

Figure 7.3 Mean ± SD of A: time to peak power production, B: cadence at maximum power over three time trials; CAF: caffeinated chewing gum, PLA: placebo, TT: time trial.

7.5.4 Heart Rate

There was no significant effect of CAF on riders' HR during the TT $F(1, 14) = 1.472$, $p = .245$, $\eta_p^2 = 0.09$ as well as, no significant interaction of condition × time $F(2, 28) = 2.415$, $p = .108$, $\eta_p^2 = 0.12$ (Table 7.4).

7.5.5 Rating of Perceived Exertion

RPE values significantly reduced $F(1, 14) = 25.020$, $p = .001$, $\eta_p^2 = 0.64$ in CAF condition (6.6 ± 1.3) compared to the placebo (7.2 ± 1.7). There was no significant interaction of condition × time $F(2, 28) = 1.437$, $p = .322$, $\eta_p^2 = 0.10$ over TTs (Table 7.4).

7.5.6 Blood Lactate

There was a significant effect of time on riders' BL values $F(2, 28) = 457.191$, $p = .001$, $\eta_p^2 = 0.97$ however, no significant interaction of condition was observed $F(1, 14) = 2.404$, $p = .143$, $\eta_p^2 = 0.15$ (Table 7.4).

Table 7.4 Mean ± SD of heart rate, RPE, and blood lactate over three BMX time trials.

		BMX TTs		
TT Variables	**Condition**	**TT1**	**TT2**	**TT3**
Heart Rate (beats·min^{-1})	CAF	176 ± 5	182 ± 4	186 ± 2
	placebo	175 ± 3	183 ± 3	183 ± 3
RPE (1-10)	CAF	6.5 ± 1.3 *	6.5 ± 1.0 *	6.7 ± 1.8 *
	placebo	6.9 ± 2.0	7.1 ± 1.2	7.3 ± 1.2
Blood Lactate (mmol·L^{-1})	CAF	10.4 ± 2.3†	14.1 ± 2.6	16.3 ± 2.1
	placebo	10.3 ± 1.4†	13.9 ± 1.2	16.2 ± 1.8

7.5.7 Coefficient of Variation

The day-to-day variation of TT variables was shown in Table 7.5.

Table 7.5 Test-retest reliability of the BMX time trial measurement.

TT variables	Average CV
Time (s)	1.2%
Power (W)	1.5%
MPW ($W \cdot kg^{-1}$)	1.5%
Cadence ($rev \cdot min^{-1}$)	1.6%
Blood Lactate ($mmol \cdot L^{-1}$)	1.8%
Heart Rate ($beats \cdot min^{-1}$)	2.1%
RPE (1-10)	1.7%

7.5.8 Blinding Evaluation

Before starting the TTs, 44% of riders in the placebo and 56% in the CAF condition correctly guessed the content of the chewing gum. While after TTs, 27% and 59% of riders in the placebo and caffeine conditions correctly identified the gum type, respectively, whereas 14% of riders declared they did not know what they had consumed.

7.6 Discussion

Caffeine's effects on short-term high-intensity activities are inconclusive (Cordingley et al., 2016). This study set out to identify the effects of CAF administration on BMX riders' TT performance. Our findings indicated that 300mg; 4.2 ± 0.2 mg·kg^{-1} caffeine delivered via chewing gum improved TT time, absolute power and MPW with riders demonstrating lower RPE. To date, few studies have identified the effects of CAF on sporting performance (Dittrich et al., 2019; Paton et al., 2015; Ranchordas et al., 2019; Russell et al., 2020); however, to the best of the authors' knowledge, this is the first to investigate caffeine intake on BMX TT performance.

Compared to placebo, CAF significantly improved TT time by 1.5%. A BMX race is generally very close and the variation of time is marginal. Based on analysis of the 2012 World Cup Supercross Series by Rylands et al. (2014) mean deviation in final positioning between 1st and 2nd place was 0.13–0.85 s, and from 1st to 3rd place was 0.38–1.52 s. In the current study, administering CAF resulted in a 0.50-second improvement in time, which could influence the final positioning in a BMX race. However, as riders' day-to-day variation for TT time were 1.2%, despite demonstrating a large effect size, the improved TT time following caffeine condition was close to the day-to-day variation. We calculated the day-to-day variation using data collected under different conditions (familiarisation and placebo) which might affect the reliability of CV. Future research might need to consider having separate baseline measurements to analyse the precise CV and provide further details on the role of CAF on BMX TT time.

In the current study, a moderate dose of CAF improved riders' absolute power by +3.5% with a large effect size. This magnitude was in line with Paton et al. (2015) who reported ~4% enhancement in sprint power output during a laboratory simulated, 10-km cycling trial, following ~3–4 mg·kg^{-1} caffeine administration. Paton et al. (2010) also showed ~6% improvement in repeated 30-second sprint performance in male competitive cyclists who consumed 240mg caffeine by chewing gum. In another experiment, Ryan et al. (2013) showed that a dose of 3 mg·kg^{-1} caffeine delivered 5-min pre-cycling by gum in trained cyclists, improved 7-kJ·kg^{-1} time-trial cycling performance. Consuming CAF in the current study helped BMX riders to produce ~40W greater peak power in TT3 compared to TT1. Increasing power production can significantly influence BMX riders' race performance (Daneshfar et al., 2020b). Specifically, at the start of the race, where gaining the front position significantly affects the overall results (Rylands et al., 2014). As chewing gum appears a fast and effective method of caffeine ingestion for athletes compared to pills/capsules, administration by this method may be particularly advantageous for BMX riders prior to racing or during recovery time.

Anaerobic power output relative to body weight (power-to-weight ratio) is a popular measure of ability among competitive cyclists (Lunn et al., 2009). Similar to peak power, we found CAF improved riders' MPW up to 3% compared to placebo. These findings are contrary to a recent study by Anderson et al. (2018a) who reported no positive effects of consuming (250mg, 3-6 mg·kg^{-1}) caffeine on anaerobic power, even though 5 out of 9 cyclists exhibited an increase in Wingate peak power during the caffeine trial. The results of the current study are in line with Woolf et al. (2008) who demonstrated ~5% improvement in MPW of Wingate test following 5 mg·kg^{-1} caffeine consumption in 18 highly trained men. Therefore, our study, alongside Woolf et al. (2008), supports the ergogenic effects of CAF on cycling anaerobic power.

The BL concentration showed a significant increase from 10 mmol·L^{-1} in TT1 to 16 mmol·L^{-1} in the TT3, which supports the highly anaerobic nature of BMX racing (Louis et al., 2013). While CAF has no ergogenic effects on BL, these findings seem to be consistent with other researchers who reported no significant effect of caffeine on BL (Anderson et al., 2018a; Glaister et al., 2012; Greer et al., 1998b; Hahn et al., 2018). In contrast, a number of studies have found a significant increase in BL following caffeine ingestion in both trained and untrained subjects (Anselme et al., 1992; Carr et al., 2008; Cordingley et al., 2016; Woolf et al., 2008). Further research is required to establish the effects of caffeine on BL during BMX TTs. While our data showed a main effect of time on HR over TTs, there was no significant effect of CAF on riders' HR. It was expected an increased HR response in CAF condition as caffeine directly reduces the parasympathetic nervous system activity (Sondermeijer et al., 2002), but in higher exercise intensities this difference tends to disappear as the sympathetic nervous system dominantly controls HR (Karapetian et al., 2012). Findings of the current study support those who reported no ergogenic effects of CAF on HR (Ryan et al., 2013; Woolf et al., 2008).

Another mechanism by which caffeine improves performance is a reduction in perception of effort (Davis et al., 2003). It is believed caffeine works as an adenosine antagonist and hence delays fatigue and improves alertness and mood (Astorino et al., 2010; Hahn et al., 2018). Stuart et al. (2005) reported the ergogenic effect became more apparent in the latter half of repeated tests. Caffeine also lowers peripheral fatigue and RPE (Sökmen et al., 2008) and provides a greater capacity to tolerate the discomfort associated with tiredness during exercise (Doherty et al., 2005). This is supported by data in the present study whereby CAF decreased riders RPE levels with a large effect size. Our findings are in agreement with researchers who reported the ergogenic benefits of caffeine on RPE (Doherty et al., 2005; Doherty et al., 2004; Glaister et al., 2018; Greenland et al., 2019). Our data may be beneficial for those competitive BMX riders with low habitual caffeine consumption, who are interested in consuming caffeine prior to training and racing to improve their performance. Future research should be undertaken to validate these findings, using elite or riders who are habitual caffeine consumers.

In the current study, all subjects received the same dosage of 300mg of caffeine and this corresponded to a range of 3.8– 4.4 $mg \cdot kg^{-1}$. We did not measure blood caffeine concentrations; therefore, the amount of caffeine absorption in the blood with different doses of caffeine remains unclear. Also, absorbed sugar from CAF in oral cavity could potentially affect performance by activating brain regions related to the sense of reward and pleasure, similar to the mechanism involved in improved performance following carbohydrate mouth rinse (de Ataide e Silva et al., 2013; Ferreira et al., 2018). Furthermore, CAF and placebo gums contained a variety of other different ingredients (e.g. artificial colours and flavours) that may have affected the study outcomes. Future research should use chewing gum with identical contents to avoid the influence of additional substances. Additionally, despite the effective blinding method, given the greater importance of the pre-TT responses compared to the post-TT responses, the percentage of riders who correctly identified the placebo beyond chance pre-TT (44%) was greater compared to post-TT (14%). We also did not measure exercise-induced pain after TTs, and the effects of CAF on riders' perception of pain remained unclear. Despite providing instruction for riders' diet, we did not control their diet and hydration during the trials, which may have affected the study outcomes and is therefore a limitation of the present study. Based on research by Foster et al. (2001), collecting retrospective recall RPE involves subjects rating the Borg CR-10 scale 30 min after experiment. We asked riders to rate their feeling immediately following TT, which could affect the validity of our RPE results. Finally, to measure performance, riders performed TT using the same BMX bike with a fixed gear ratio. As riders typically use their personal bike and compete with others in a race, this might affect the power production and their overall performance.

This is the first study to explore the effects of CAF on BMX performance. Our novel findings demonstrated that CAF containing 300mg caffeine and 6 g of sugar vs. non-caffeinated sugar-free placebo gum improved TT time, boosted riders' power up to 3%, and decreased their post-TT RPE. It may be appropriate to consume the current caffeine amount 10-min prior to a BMX race, to improve performance by enhancing power production and reducing perception of exertion, particularly where successive races are required.

Chapter 8

Discussion

8 Discussion

The overarching aim of the current thesis was to investigate the physical and physiological demands of BMX racing in both laboratory and field conditions, and assess potential ways of improving key performance features using a multidisciplinary sport science approach. A comprehensive review of the literature on BMX riders' performance related characteristics and race analysis in BMX cycling, has highlighted that there is a considerable lack of peer reviewed research which needs addressing.

Based on the aforementioned gaps in the literature, the objective of this thesis was to firstly describe the physical demands of BMX riders measured in the laboratory (Chapter 3), and evaluate the physiological demands of undertaking successive time trials (Chapter 5). This approach lead to identify the most important performance indicators in BMX cycling. Then utilising mobile power meter technology, simulated time trial performance was analysed (Chapter 6). The outcomes from these initial studies informed subsequent research in which a specific BMX cognitive training in the form of MI practice was applied to highlight the role of psychology on riders' time trial performance (Chapter 7). Finally, the role of pre- time trial consumption of CAF was examined to see the effects on power production and time trial performance (Chapter 9). The following discussion describes the outcomes of these series of studies.

To design an optimal training program in which the physical, technical and tactical elements are considered, specific demands of the competition must first be understood. As a foundation for subsequent research, the initial series of investigations (Chapter 3 and 4) described the physical characteristics of BMX riders and race demands. More specifically, to predict BMX race performance, we employed a multidimensional approach using laboratory-based measures. Twenty-eight variables including, somatotype, anthropometric, flexibility, muscular strength, jump power, and cycling power output were measured in the laboratory condition. Our findings showed that across all anthropometric, strength, and physiological categories, 87% of BMX race finish time variation could be explained by the combination of power-to-weight ratio, relative Back-Leg-Chest strength, and arm span. Although this study supported the importance of muscular power, riders' anthropometry and muscular strength were also introduced to the BMX literature as key performance indicators. BLC strength help riders to better control over the bike while racing, specifically in the technical sections, by increasing stability and balance. In addition, as BMX bike dimensions do not vary, riders' height and arm span could affect mechanical efficacy and subsequently overall race performance. To determine the physiological demands and metabolic pathways of BMX racing (Chapter 4), we measured riders' performance over six simulated time trials on an actual BMX track. By monitoring power output and HR, post lap VO_{2peak}, RPE, BL, and lap time, the physio-metabolic characteristics of racing and potential correlations between lap variables were highlighted.

Key findings were that a) BMX time trial time was significantly correlated with mean PWR but the strength of this association decreased as successive laps were performed. b) Riders demonstrated a high contribution of aerobic metabolism during laps and showed a significant correlation with mean lap times. This association indicated an incremental trend. c) Mean BLr was significantly correlated with mean lap times, and the correlation between BLr and time in each lap was stronger in the latter laps. According to our results, despite the short (~35s) cycling time in each BMX lap, both aerobic and anaerobic energy systems were associated with faster performance. Collectively, the results of these investigations suggest that BMX coaches and practitioners should consider the importance of muscular strength, cycling anaerobic power production, as well as aerobic fitness when designing conditioning programs. Riders anthropometry also should be taken in to account during talent identification processes and when recruiting new riders. The current approach will prove useful in expanding our understanding of how different physio-metabolic variables play roles in BMX racing.

Due to the importance of anaerobic power in BMX racing, the purpose of Chapter 5 was to analyse riders' power production on different track segments, and their potential correlation with overall performance. Specifically, a more thorough evaluation of power distribution during the race was reported.

Firstly, our results demonstrated a significant association between peak power and average power with race time, and highlighted the significance of the first straight in a BMX track and its impact on overall time trial performance. Secondly, time cornering demonstrated a positive correlation with riders' overall time trial time. Our data also showed that a second peak (72% of race peak power) occurred while riders pedalled around the first corner, after an explosive power production at the start. Lastly, we provided the first report on the power data binning in BMX cycling, showing the distribution of riders' power over the time trial period. Riders spent ~35% of the race time in >500 W sprint zone which highlighted the importance of the anaerobic power and energy system in a BMX race. On the other hand, non-pedalling periods of a race equated for ~40% of the race time, as well as a period of producing very low power <100 W which can be considered insignificant power output. In a BMX race, pedalling is often blocked by jumps, curves, and other changes in the track, which affects the power production. By reporting the average power (zero values excluded) and its association with race time, we demonstrated that beside the importance of a powerful start and generating maximum power in the first few seconds of the race, maintaining power and velocity throughout the race is another critical factor. Time-course power analysis in the current study confirmed the previous beliefs around the intermittent nature of BMX racing. It is important for BMX coaches and riders to be aware of the role cadence and power distribution play in a race, for training programmes and gear selection.

There is a necessity for understanding the role of cognitive training in BMX racing performance. MI is a popular method utilised by sport psychologists and has attracted much research attention over the past few years. The aim of Chapter 6 was to investigate the effectiveness of 4 weeks of specific MI training in addition to routine track training, on BMX riders' time trial performance. MI training did not significantly improve riders' time trial time; however, there was a trend of faster time trial times for riders in the MI condition. In the first time trial, riders finished the time trial 2.4% and 4% faster than baseline and control conditions, respectively. In a BMX race, competition is generally very close and any minor improvement in finish time, relative to other competing riders, can significantly affect final placing. Future research is required to investigate the impact of MI training on overall race performance. Our results revealed a large ~4% improvement in relative peak power in the first time trial compared to the baseline and control conditions. Riders in MI condition also reached ~3% more relative peak power in time trial 1 compared to time trial 2. Rider imagery ability also improved across conditions. Having a better imagery ability can significantly influence MI effects, so we measured this variable pre and post intervention, however, there was no significant correlation between imagery ability and time trial performance. This was the first study to determine the effects of MI on BMX time trial performance. BMX coaches and riders should consider using MI training alongside their routine BMX training, as MI can be considered deliberate practice, where highly structured and purposeful practice is applied to improve race performance.

With the findings of Chapters 3, 4 and 5, showing the significant role of power production on BMX racing, applying different strategies should emphasise the development of this variable. As such, the focus of Chapter 7 was to determine whether consuming caffeine in the form of chewing gum, pre-BMX race, would be effective and provide ergogenic benefits for BMX riders. It was assumed that, if caffeine enhances short-duration, high-intensity performance by increasing anaerobic power and sprint speed, then BMX riders may benefit from the consumption of CAF. The performance measures (dependent variables) in this study included time trial time, absolute peak power, maximal power-to-weight ratio, time to peak power, cadence at peak power, BL, HR, and post time trial RPE. Our findings indicated that 300 mg caffeine administered by chewing gum improved time, absolute power and power-to-weight ratio with riders demonstrating lower RPE. Compared with placebo, CAF significantly improved time trial time by 1.5% and riders' absolute power by +3.5% with a large effect size. As chewing gum appears to be a fast and effective method of caffeine ingestion for athletes compared with pills/capsules, administration by this method may be particularly advantageous for BMX riders prior to racing or during recovery. This was the first study to explore the effects of CAF on BMX performance. It may be appropriate to consume caffeine 10 min prior to a BMX race to improve performance by enhancing power production and reducing perception of exertion, particularly where successive races are required.

The series of studies comprising this thesis provide comprehensive data for using a multidisciplinary approach detailing physical and physiological demands of BMX riders and racing, analysis of race performance, effectiveness of cognitive training and CAF supplementation on BMX race performance. Current outcomes should be considered by BMX coaches and practitioners when planning their annual training programmes and when determining race strategies.

Chapter 9

Conclusion

9 Conclusion

The outcomes of this thesis have provided an insight into several areas BMX coaches and practitioners should consider when assessing and programming training for their athletes.

- To identify the key performance indicators of BMX racing, a multidimensional approach is required. Alongside maximising power production, enhanced muscular strength and anthropometrical features are also important.

- In order to maximise the power-to-weight ratio, body fat percentage should be monitored as a higher than desirable body fat percentage could negatively influence race time and power production. Therefore, weight management should be considered by both riders and conditioning coaches.

- Despite BMX competition day consisting of 4-6, 30-50 s cycling races, the sport is significantly influenced by aerobic capacity. It appears that aerobic fitness is important and can influence riders' recovery between successive races.

- BMX riders should therefore focus on improving successive BMX laps via greater improvements in H^+ regulation and natural buffering by developing aerobic capacity.

- A power analysis demonstrated 35% of race time is spent sprinting (> 500 W). By continuously recording power output, the exact demands of a race can be more accurately quantified. The intensity and duration (or both) of training can therefore be modified to be more race specific.

- It is important for BMX coaches and riders to be aware of the role that cadence has in a race and this provides an insight for their training intensity as well as gear selection.

- In a BMX race, pedalling is often prevented by jumps, curves, and other changes in the track, which affect power production. Maximising the generation of power in the corners, or when pedalling is possible, would assist riders maintain speed and overcome upcoming obstacles.

- The initial power from the start helps BMX riders pick the best position in the race. Pedalling performance in the first corner can then minimize any loss in speed, and provides a chance to maintain speed by generating more power.

- Cognitive components of the MI script, which refer to the imagery of race strategies, could lead to higher confidence and decreased anxiety levels.

- MI is a safe addition to BMX training and can be used supplement normal training. Emphatically, as MI improves power production and can be a genuine learning approach, coaches can use MI training as an alternative tool for teaching new techniques or while training young riders.

- Caffeine enhances short-duration, high-intensity performance by increasing anaerobic power generation.

- A moderate dose of caffeine delivered by chewing gum can improve BMX time trial performance by improving time, power production, and decreasing RPE.

- CAF has no ergogenic effect on BMX riders’ HR and BL measured in time trial.

9.1 Limitations

Despite the useful implication of the findings of this thesis, the following limitations are noted:

- These findings are limited to sub-elite competitive BMX riders.

- The sample size of the current studies were relatively small due to limited competitive BMX riders available at the time of study.

- All the power output data in the current thesis was measured using the same bike. We used the same bike to standardise the data collection and control the measurement.

- Track performance was measured by a time trial where each rider completed the laps individually. In an actual BMX race, up to eight riders race together.

9.2 Future Research Directions

- Data regarding physical and physiological demands of elite BMX riders in comparison with sub-elite data would help the talent identification and development process.

- A better understanding of training demands of BMX riders would help to monitor progress and effectiveness of their training.

- Quantifying the race physiological demands of various level of competition, especially at the age group level and in female riders, would assist conditioning coaches prescribe level and gender-specific fitness and recovery programs.

- Quantifying longitudinal changes in physiological and physical characteristics of BMX riders would assist coaches in planning and evaluating conditioning and testing strategies.
- Measuring technical elements and investigating the contribution of technical level compared to physical fitness on race performance would be useful for coaches to have a balance of physical and technical training period.

- Applying different recovery strategies between successive races would assist riders to discover better recovery applications during competition.

- Due to the importance of power production, applying different power-based training, including Olympic weight lifting derivatives and its effectiveness, would provide better understanding for BMX conditioning coaches.

- Practical guidelines to individualise conditioning and recovery programmes based on the BMX race demands need development and evaluation.

- Future research should apply different cognitive strategies including self-talk, goal setting or MI to identify the greater magnitude of effect on BMX race performance.

- The effectiveness of supervised MI training programmes at the track before BMX training should be investigated.

- CAF in future research should be consumed during the recovery period to evaluate its effectiveness on successive races.

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12 Appendix 2 PhD Publications

Journal of Science & Cycling
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Original article

Prediction of track performance in competitive BMX riders using laboratory measures

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Abstract: Identifying key physiological factors is essential in cycling; however, the unique nature of BMX decreases the validity and transferability of research findings from other cycling disciplines. Therefore, this study highlighted the physical and physiological characteristics of BMX riders that could influence track performance. Fifteen sub-elite BMX riders (male n = 12; age 18.3 ± 3.3 and female n = 3; 17.7 ± 5.7 years) undertook a battery of laboratory tests on three different occasions, including body composition, upper and lower body strength, flexibility, sprint and aerobic capacity measures. On a separate day, participants completed three full lap sprints on an outdoor BMX track. Correlation and multiple linear regression analyses were performed to develop predictive models of performance across the laboratory tests and race time. The final model indicated power to weight ratio, relative back-leg-chest strength and arm span explained ~87% of the variability in finish time (adjusted $R2 = 0.87$, $p < .01$). These findings highlighted the importance of a multidimensional approach for developing BMX race performance. Coaches should prioritise these variables in their training programs and selection of future talents. However, further physiological and biomechanical investigation is needed to validate current findings, particularly among elite riders.

Keywords: Peak Power, BMX Time Trial, Physiological Demand, Anthropometry

1. Introduction

Bicycle Motocross (BMX) is a relatively new Olympic sport since 2008, which is built on the premise of fast racing around off-road tracks on a bicycle smaller and lighter than a road bike or mountain bike. A BMX race over a 300-400m dirt track begins with the drop of the starting gate, after which up to eight riders pedal down a 5-8m slope. Riders then face several large jumps, banked turns, and smaller jumps in quick succession. In a BMX race, riders combine the cycling periods with technical non-pedaling periods known as manualling and pumping in which the upper body manoeuvres the bike. It is believed that both physiological and technical proficiency of riders contribute to race performance and riders' success (Rylands et al., 2017a).

Given the high technical and physical demands of BMX, previous research highlighted the importance of gaining the front position of the race group by the end of the first jump. This gives riders a distinct advantage to best navigate the upcoming obstacles and contribute with a faster finish time (Cowell et al., 2012b). To gain the front position, BMX riders attempt to apply a maximum power effort using the leverage and strength of their upper and lower body (Herman et al., 2009; Mateo et al., 2011; Rylands et al., 2014). Factors that could affect power output such as gear ratio (Rylands et al., 2017b), optimal cadence (Rylands et al., 2017c), and the maximal torque and cadence relationship (Debraux et al., 2013; Gardner et al., 2007) have also been investigated. Despite this, research of physiological demands and performance predictors are scarce, and BMX coaches require specific data (Rylands et al., 2019).

Identifying key performance indicators is considered an important step to increase the efficacy of training programs. Bertucci et al. (2011) evaluated the relationship between laboratory measures, including Counter Movement Jump (CMJ), Squat Jump (SJ), seated and standing 30 second Wingate sprints, with subsequent race performance. Their results demonstrated a moderate relationship between power output and 80m sprint from a stationary start on levelled ground. However, this research was suffering from ecological validity. For instance, the race performance was measured only to the end of the first straight section (75m) and not over the whole track, therefore, some findings may be missed by negating the rest of the race distance. In addition, with BMX being an intermittent cycling activity, where only 30-40% is devoted to pedalling, a continuous 30 second Wingate test may not be a good predictor of BMX performance (Cowell et al., 2011). Furthermore, while the lower body power output significantly associated with overall performance, success in BMX racing might also be influenced by factors other than just lower body power. For instance, riders' anthropometry (Grigg et al., 2017), muscular strength (Cowell et al., 2012b), and aerobic capacity (Louis et al., 2013).

BMX race analysis showed that between ~ 70% of the race time is spent jumping, coasting, or pumping (Cowell et al., 2011). Rylands et al. (2017a) showed that upper body pumping technique could improve the finish time by 20% compared to the non-pumping technique. Furthermore, Baker et al. (2001) stated that upper body strength significantly contributes to cycling peak power. Their study demonstrated that the intensity of the electrical activity recorded for the forearm musculature during sprint cycling was similar to that recorded during a maximum voluntary hand grip contraction. By pulling the handlebar, the centre of body mass is maintained at a constant vertical level, so that leg extension can be directed to pushing down on the pedals and facilitate the acceleration phase of performance (Dore et al., 2006).

Intuitively, based on race movement pattern, it could be argued that overall muscular strength and the anthropometric profile of riders could improve leverage and offer functional advantages to BMX riders. Given the limited data available on physiological demands of BMX racing, a holistic approach to identifying contributing factors to riders' performance seems most appropriate. This information could assist coaches in prioritising specific components of training for annual periodization and selecting future talents. Therefore, the purpose of the present study was to investigate the relationship between anthropometrical features and laboratory-based assessments of strength and power, with track performance.

2. Methods

Participants

Fifteen sub-elite BMX riders (12 males and 3 females; age: 18.3 ± 3.3, 17.7 ± 5.7 years; height 177 ± 5.8, 164 ± 3.6 cm; mass 69.2 ± 6.4, 67.8 ± 13.9 kg; body fat percentage (BF%) 13.3 ± 4.4, 26 ± 7.5; muscle mass 34.4 ± 3.2, 28.8 ± 1.6 kg; training experience 7.5 ± 2.5, 6.4 ± 2 years for males and females respectively) volunteered to participate in this study. All participants were informed about the study protocol and potential risks and provided written consent by the Declaration of Helsinki. Parental consent was also obtained for participants under the age of 18. This study was approved by the Human Ethics Committee of the University of Canterbury.

Design

In this cross-sectional study, the relationships between laboratory results and track performance were investigated using multivariate analysis over three different occasions. Firstly, participants had a familiarisation session of all laboratory testing procedures, as well as anthropometric measurement. The following day, in the second laboratory session, maximal strength and cycling sprints were measured. Finally, 48 hours later, participants' aerobic capacity was tested. The track performance was measured one week later and described as the time taken to complete three all-out efforts on a 342m outdoor BMX track.

Anthropometric assessment

Body mass (Seca Quadra 808 digital scales, Birmingham, UK), height (Seca 213 stadiometer, Birmingham, UK), arm span, hand dimensions (Lufkin W606PM anthropometric tape, SPARK, USA), and sum of seven skinfolds including triceps, subscapular, biceps, supraspinale, abdominal, thigh and medial calf (Harpenden Callipers Holtain, Crymych, UK) were assessed by a level two anthropometrist following the International Society for the Advancement of Kinanthropometry (ISAK) testing protocols (Marfell-Jones et al., 2012).

Muscle mass and BF% were determined using Bio-electrical Impedance (Inbody 230, Seoul, Korea), which its validity and reliability have been approved by Von Hurst et al. (2016). The somatotypes of participants were assessed according to the Heath-Carter method (Carter et al., 1990) using the Somatotype 1.2.6 program (MER Goulding Software Development, Geeveston, Australia).

Strength assessment

Handgrip strength (HGS) was measured using a digital dynamometer (Jamar Plus Digital-Dynamometer, Chicago, USA) according to the American Society of Hand Therapists (Fess et al., 1981). Participants held a dynamometer in their hand with the arm held straight and maximally squeezed for three seconds. The maximum strength of the three attempts for each hand was recorded (Mathiowetz et al., 1984).

Back-leg-chest strength

A calibrated Back-Leg-Chest (BLC) strength dynamometer (Mentone, Victoria, Australia) was used to assess isometric muscle strength. The length of the chain was adjusted according to the participants' height with their knees and hips flexed slightly and with their lower back in an appropriate lordotic curve. Participants lifted in a vertical direction with a continuous isometric contraction of the extensors of the knees, hips, and lower back. After demonstration and familiarization, three attempts were performed, each followed by a 30-second rest period. The best of the three attempts was recorded (Ten Hoor et al., 2016).

Maximal leg press, leg extension and bench pull strength tests (1-RM)

A one repetition maximum test (1-RM) was used to estimate the maximal strength of bench pull, leg press and leg extension using a cable machine. Prior to testing, a warm-up of 6 to 10 repetitions at approximately 50% of the participants estimated strength was undertaken. The 1-RM test was initiated two minutes post-warm-up. Using the protocol employed by Brzycki (1993), participants attempted to lift each weight a maximum of 10 times. If 10 repetitions were achieved, a higher weight was tested following a 5-minute recovery. Whereas when a participant was only able to complete less than 10 repetitions, this number was entered into the maximum repetition calculations.

$$\text{1-RM} = 100 * \text{load rep} / (102.78 - 2.78 * \text{Rep})$$

Where: load rep = workload value of repetitions performance in kg.

Rep = number of repetitions performed.

Leg power tests

The correct technique for SJ and CMJ were demonstrated and explained to each participant by a qualified biomechanist. The SJ tests were performed in an upright standing position with hands on the hips and flexed knees. This position was maintained for three seconds before participants jumped as high as possible, without any counter-movement action. The CMJ started with an upright standing position with hands unrestricted. The participants were encouraged to bend their knees to approximately 90◦ and use their arm to achieve the maximum height with no delay at their lowest position (Daneshfar et al., 2018). After a standardized warm-up of 2-3 repetitions of both SJ and CMJ, participants were asked to perform three jumps with a passive recovery of 1-min in between each jump. The highest jump of the three attempts was recorded. Participants were instructed to repeat any incorrectly performed jumps.

Laboratory leg power assessment

Each participant performed three 10-second standing cycle sprints on a Wattbike Pro (Giant 2015, Nottingham, UK) which was calibrated according to the manufacturers' guidelines. The air and magnet resistance was set at level 1. Through the use of a load cell, the Wattbike calculates the force that the cyclist applies through the cranks onto the chain at 100Hz. Power output is then calculated as the sum of all of the force applied to the chain. The highest peak power of the three attempts was recorded, as well as the average 10-second power, max cadence, time to peak power, minimal power, and fatigue index. The bar height and stem length were adjusted to each participant's preferred position, while the seat was set at the lowest position so it would not interfere when performing each sprint. Each participant performed their usual warm-up which included both seated and standing short cycling sprints. Participant were encouraged to reach maximal power as fast as possible while performing each sprint from a standing stationary position using their preferred leg in the lead position. A rest period of 10 minutes was employed between each sprint (Gardner et al., 2007).

Maximum Aerobic Capacity (VO2max)

An incremental intensity bike test, undertaken to exhaustion, was used to determine VO2max. Following a 6-min warm-up at 100 W, power was increased by 30 W per minute until volitional exhaustion occurred, with participants choosing their preferred cadence. During the test, oxygen uptake (VO2), minute ventilation (VE), and respiratory exchange ratio (RER) were continuously measured breath-by-breath with a gas exchange analyzer (K5, Cosmed, Italy) which was pre-calibrated in accordance with the manufacturer's instructions. To determine VO2max, these three conditions were required: a plateau in VO2 despite an increase in power output, a RER above 1.1, and a heart rate (HR) above 90% of the participants' age-predicted maximal HR. Peak VO2max was taken as the highest sampled average of the 30 second reading (Howley et al., 1995).

On track sprint assessment

Two weeks after completing their laboratory testing, participants were tested at the Christchurch BMX track, in New Zealand. Prior to testing, they performed a structured self-paced warm-up consisting of 4-6 standing short sprints. Three full lap races were then undertaken using the same BMX bike (gear ratio of 43/16). The track included a 5m high start ramp and a standard electronic start gate was employed. Lap time was recorded using two pairs of photocells (NEOtm Swift Performance, Queensland, Australia) positioned at the start gate and on the finish line. A 15-minute passive recovery was undertaken between each of the three races, and the fastest finish time of three races was recorded.

Blood Lactate

Blood lactate concentration (mmol.L-1) was measured using a Lactate Pro2 analyzer (Arkray, Koyoto, Japan) while a finger prick was taken before warm-up (baseline value) and 3 min after the sprint tests (Tanner et al., 2010).

Statistical Analyses

Data were analysed using SPSS 25 (SPSS, An IBM Company, Amarouk, NY) and presented in mean ± SD. All variables were assessed for normality using the Shapiro-Wilk test. The Pearson's correlation coefficients and simple linear regression models were used to assess the relationship between the physical and physiological lab measures (independent variable) with the BMX finish time (dependent variable), as well as to screen for independent variables to be included in the multiple linear regression model (Table 1). Forward stepwise multiple linear regression was conducted to identify the best model. In addition, the typical error of estimate and 95% Confidence Limits (CL) were used to describe predictive accuracy.

Table 1. Dependent and selected independent variables

Dependent Variable	
Time to finish	**time to completion of the race (s)**
Selected independent variables	
Arm span	distance between the middle finger of each hand while the arms are outstretched (cm)
BF%	percentage of whole-body fat component (%)
Muscle mass	muscle mass (kg)
Relative leg press 1RM	one repetition maximum ($kg.kg^{-1}$)
Relative bench pull 1RM	one repetition maximum ($kg.kg^{-1}$)
BLC strength 1RM	one repetition maximum (kg)
Maximal HGS	hand grip strength (kg)
SJ	squat jump
Power to weight ratio	power to weight ratio ($W.kg^{-1}$)
Maximum cadence	cadence at peak power ($revs \cdot min^{-1}$)
VO_2max	maximum oxygen capacity ($ml.kg^{-1}\ min^{-1}$)

3. Results

Variables were normally distributed and descriptive data for lab and track performance is presented in Table 2 separated by gender. Pearson's correlation coefficients were significant between finish time and BF% (-0.727), endomorphic value (0.763), relative back strength (0.725), SJ (-0.730), and maximum cadence (-0.756), respectively (Table 3).

Following the identification of collinear variables, those variables (e.g. height, sit and reach, relative leg extension) that could not be retained in any models were omitted from the results. Forward multiple regression was performed for finish time with anthropometrical, and physiological variables. No violations of the assumption of linearity,

homoscedasticity, and outliers were observed (Table 4).

The strongest model to predict the BMX race performance displayed a good fit (adjusted R2 = 0.867; $p < .001$). This model utilised three independent variables: arm span, relative BLC strength and power to weight ratio which, when taken together, were responsible for 87% $F(3, 11)$ of the explained variability in the finish time of the race (Table 5).

Table 2. Descriptive statistics of the lab and BMX track (mean ± SD)

	(Male, N=12)	(Female, N=3)
Somatotype and Anthropometric		
Endomorph	2.6 ± 0.4	5.3 ± 1.8
Mesomorph	4.9 ± 1.1	4.4 ± 1.7
Ectomorph	2.5 ± 0.8	1.6 ± 1.0
Arm span (cm)	178.7 ± 8.4	161.0 ± 5.8
Maximal hand dimension (cm)	22.4 ± 1.2	19.3 ± 2.1
Flexibility and Laboratory Strength		
Sit and reach (cm)	14.8 ± 5.8	18 ± 1
Leg extension 1RM (kg)	117.2 ± 13.0	83 ± 24
1RM relative leg extension ($kg \cdot kg^{-1}$)	1.7 ± 0.1	1.2 ± 0.2
1RM bench pull (kg)	62 ± 12.5	36 ± 9.9
1RM relative bench pull ($kg \cdot kg^{-1}$)	0.9 ± 0.1	0.5 ± 0.1
1RM leg press (kg)	177. 6 ± 30	125.7 ± 87.0
1RM relative leg press ($kg \cdot kg^{-1}$)	2.5 ± 0.3	1.7 ± 1.1
Maximal HGS (kg)	46.4 ± 5.6	31.3 ± 4.7
BLC strength (kg)	145.7 ± 20.0	101 ± 10
Relative BLC strength ($n \cdot kg^{-1}$)	2.1 ± 0.2	1.5 ± 0.2
CMJ (cm)	54.7 ± 10.7	32.3 ± 0.7
SJ (cm)	40.3 ± 6.3	24.67 ± 0.6
Laboratory Bike Test		
Peak power (W)	1220 ± 177	837 ± 138
Power to weight ratio ($W \cdot kg^{-1}$)	17.6 ± 1.8	12.5 ± 1.2
Average power (W)	1071 ± 165	718 ± 109
Relative average power ($W \cdot kg^{-1}$)	15.5 ± 1.9	10.7 ± 1.4
Maximum cadence ($revs \cdot min^{-1}$)	152 ± 10	125 ± 8
Time to peak power (s)	0.8 ± 0.6	0.7 ± 0.3
Minimal power (W)	948 ± 143	649 ± 60
Relative minimal power ($W \cdot kg^{-1}$)	13.7 ± 1.6	9.8 ± 1.7
Fatigue Index (a.u)	27.2 ± 7.5	18.8 ± 8.8
VO_{2max} ($ml \cdot kg^{-1}\ min^{-1}$)	43.3 ± 5.8	35.0 ± 5.3
RPE	9.7 ± 0.4	8.7 ± 0.6
Resting blood lactate ($mmol \cdot L^{-1}$)	2.2 ± 0.5	2.5 ± 0.7
Post 3 min blood lactate ($mmol \cdot L^{-1}$)	10.9 ± 2.7	9.5 ± 1.1
BMX Track Performance		
Finish time (s)	36.39 ± 0.70	40.71 ± 0.80
HR on the track (% of HR Max)	88.5 ± 3.9	85.2 ± 3.7

Table 3. Pearson correlation coefficient matrix

	TTF	AS	BF%	MMS	RBP	RLP	DHG	RBLC	SJ	PWR	MCad	VO2max
AS	-0.676 †	-										
BF%	0.727 †	-0.472	-									
MMS	0.629*	0.783 †	-0.536	-								
RBP	-0.645 †	0.435	-0.525 *	0.657 †	-							
RLP	-0.543 *	0.583*	-0.065	0.388	0.529*	-						
DHG	-0.699 †	0653 †	-0.264	0.510	0.607 *	0.808 †	-					
RBLCS	-0.725†	0.303	-0.681 †	0.561 *	0.592 *	0.191	0.516 *	-				
SJ	-0.730 †	0.434	-0.464	0.522	0.678†	0.487	0.536*	0.544*	-			
PWR	-0.868 †	0.459	-0.636 *	0.568 *	0.749 †	0.395	0.475	0.644 †	0.786 †	-		
MCad	-0.756 *	0.767	-0.515 *	0.680 †	0.567 *	0.518	0.585 *	0.603 *	0.541 *	0.642 †	-	
VO2max	-0.647 †	0.304	-0.264	0.463	0.463	0.404	0.593 *	0.672 †	0.522 *	0.655 *	0.534 *	-

TTF: Time to Finish; AS: Arm Span; BF%: Body Fat Percentage; MMS: Muscle Mass; RBP: Relative Bench Pull; RLP: Relative Leg Press; DHG: Dominant Hand Grip; RBLC: Relative Back-Leg-Chest Strength; SJ: Squat Jump; PWR: Power to Weight Ratio; Mcad: Max Cadence; VO2max: maximum oxygen uptake normalized by body mass (ml.min-1.kg-1); *Significant at 0.05; † significant at 0.01

Table 4. Multiple regression model to predict time to finish of the simulate BMX race

Anthropometric Variables				
Coefficient				
	B [95%CI]	(β)	sr^2	
Predictor Variable				
Arm Span	-0.161 [0.177, 0.055]	-0.334	0.039	
Body Fat%	0.136 [-0.016, 0.256]	0.502	0.183	
Model Summary				
Observation	R^2	*Adjusted* R^2	$F(3, 11)$	p
15	0.676	0.588	5.22	.005
Strength Variables				
Coefficient				
Predictor Variable	B [95%CI]	(β)	sr^2	
Relative Bench Pull	2.748 [-6.555, 4.756]	0.106	0.372	
Relative leg press	1.012 [-3.491, 1.606]	-0.165	0.021	
Relative BLC Strength	1.361 [-6.443, 0.170]	-0.466	0.133	
Maximal HGS	0.076 [-0.231, 0.168]	-0.200	0.004	
Model Summary				
Observation	R^2	*Adjusted* R^2	$F(4, 10)$	p
15	0.702	0.583	5.90	.011
Physiological Laboratory Variables				
Coefficient				
Predictor Variable	B [95%CI]	(β)	sr2	
SJ	0.048 [-0.127, 0.086]	-0.092	0.003	
Power to Weight Ratio	0.176 [-0.777, 0.010]	-0.537	0.081	
Maximum Cadence	0.023 [-0.091, 0.10]	-0.312	0.054	
VO2max	0.051 [-0141, 0.088]	-0.091	0.005	
Model Summary				
Observation	R^2	Adjusted R^2	F(4, 10)	p
15	0.828	0.759	12.01	.001

Unstandardised (B), and Standardised (β) Regression Coefficients, and Squared Semi-Partial correlations (sr^2) for each predictor in a regression model.

Table 5. Final Predictors

Coefficient				
Predictor Variable	B [95%CI]	(β)	sr^2	
Arm Span	0.020 [-0.591, 0.162]	-0.349	0.096	
Power to Weight Ratio	0.079 [-0.106, -0.019]	-0.528	0.144	
Relative BLC Strength	0.726 [-3.190, -0.007]	-0.349	0.045	
Model Summary				
Observation	R^2	*Adjusted* R^2	*F(3, 11)*	*p*
15	0.896	0.867	31.55	.001

4. Discussion

To predict BMX race performance, we applied a multidimensional approach using laboratory-based measures. Notably, our findings displayed that across all the anthropometric, strength, and physiological categories, 87% of BMX race performance variation could be explained by power to weight ratio, relative BLC strength, and arm span. Coaches and cyclists can benefit from these findings as they demonstrate the factors that may influence BMX race result and could also be considered in talent identification processes.

The ability to generate maximum power in the first few seconds is vital for success in a BMX race. Rylands et al. (2014) analysed the 2012 UCI BMX World Cup series data and showed a strong correlation between the riders' position in the first 8–10 s of the race and their eventual finish line placing. In the current study, we applied a 10 s laboratory cycle sprint test to measure power. The strong correlation found between 10 s power to weight ratio and finish time in our study supported the importance of power on the rider's final position.

Power to weight ratio is a method of comparing one athlete's ability to produce power to another (Rylands et al., 2013). Riders with a large power to weight ratio can generate a substantial amount of force when the gate drops in the BMX race. Specifically, having a higher rate of force development (RFD) allows riders to reach a higher level of force in the early phase of muscle contraction (Debraux et al., 2011). This ability, when combined with quick reaction time, potentially assists a rider to have a greater chance of gaining the front position, which is a key factor for success in BMX racing.

Rylands et al. (2013) reported power to weight ratio of 21.29 ± 0.8 W.kg-1 and 16.65 W.kg-1 in 5 male and 1 female elite British BMX cyclists respectively, which was measured on a 50m track sprint test. The authors concluded that power to weight ratio might affect BMX riders' velocity, flight time, and distance travelled in the air while competing on the BMX track. The male BMX riders in the current study had a mean power to weight ratio of 17.6 ± 1.8 W.kg-1, in contrast with the female riders 12.5 ± 1.2 W.kg-1 for the three laboratory sprint tests. The highest laboratory correlation with finish time on the BMX track belonged to power to weight ratio ($r = 0.87$; $p < .01$) and this was higher than the correlation ($r > 0.70$) found by Bertucci et al. (2011). In addition, the absolute male peak power value in our study was 123 W and 748 W lower than Spanish and French elite riders (1343 ± 68 W and 1968 ± 210 W) respectively (Bertucci et al., 2011; Mateo et al., 2011). The lower peak power output in our study may be related to a younger rider age or differences in testing procedures. It could also be explained by lower (regional) competitive level as previous research has found power of national-level riders is 28% higher compared to regional riders (Bertucci et al., 2007).

There was a significant negative correlation between finish time and BF% ($r = -0.73$, $p < .01$). Additionally, BF% was significantly correlated with power to weight ratio ($r = -0.64$, $p < .05$). Milašius et al. (2012) reported that BF% of the elite female BMX cyclist was ~23%, which was higher than elite track cyclists. In the current study, female riders had 26 ± 7.5 BF%, which was higher than both elite BMX rider and track cyclists. The excess fat component could negatively affect power to weight ratio and influence race performance. Considering these findings, riders and conditioning coaches should monitor and maintain an optimal BF% to maximise power to weight ratio.

Generally, our findings were aligned with previous research that reported lower limb power (power to weight ratio) is an important factor in BMX (Cowell et al., 2012a; Debraux et al., 2013; Rylands et al., 2017b; Rylands et al., 2017c). Additionally, Debraux et al. (2011) reported that results of CMJ, 8 seconds seated sprint cycle test, and 30 second Wingate were three performance-related factors ($R2 = 41$ to 66%) during the 5 to 75 m of initial straightaway of the BMX track. Given that multiple factors explain BMX performance, we found a combination of riders' lower limb power, strength and anthropometric characteristics could have a stronger prediction (adjusted $R2 = 0.87$; $p < .001$) of the variability of BMX race performance. These results are essential for BMX coaches and practitioners while planning conditioning training to improve riders' performance.

Skeletal muscle strength is fundamental in many sports and exercise activities. The BLC strength test has been reported as a reliable measure for overall muscular strength (Ten Hoor et al., 2016). There are similarities between the BLC test, BMX movement patterns, and muscular recruitment across the entire race. In particular, at the start of a race before initiating any movement, the riders' body posture is almost identical to the BLC strength test where they draw their hips towards the handlebars to keep their balance (Kalichová et al., 2013). Movement patterns during a BMX race demand high muscular strength in both the leg and back muscles. This can assist riders to have a powerful start, as well as the ability to stabilize the bike during technical movements such as pumping, jumping and facing obstacles in the entire race (Rylands et al., 2017a). In our study, relative BLC strength had the highest correlation ($r = -0.73$, $p < .01$) with BMX performance compared to other strength tests and hence, it was presented in the final model. Having higher relative BLC strength allows riders to apply their upper body forces on the bike to generate more speed. It is worth noting that we examined the influence of different physiological measurements on BMX performance. However, further physiological and biomechanical investigation is needed to validate current findings, particularly among elite riders.

Arm span was significantly correlated with the finish time ($r = -0.68$; $p < .01$) and appeared in our final model. The correlation between arm span and athletic performance has been investigated before. Lockie et al. (2018b) reported that individuals with a longer arm span and a shorter leg length were able to reach the peak power and velocity sooner during the deadlift. In a BMX race, riders with longer arms might be able to apply the upper body force on the bike more efficiently compared to riders with shorter arms. It can also be assumed that riders with longer arms can pump a further distance and generate more speed during the pumping technique where riders are neither pedalling nor jumping to increase their speed. However, another study reported that having a longer arm span resulted in more work during a bench press as they need to move the bar further (Lockie et al., 2018a). Therefore, in a BMX race performing more work could potentially create more fatigue and negatively influence race performance. Riders' physique varies between different cycling disciplines, for instance, sprint cyclists are significantly heavier, and have larger chest, arm, thigh and calf girths than endurance cyclists (Craig et al., 2001). As the BMX bike dimensions do not vary, riders' height and arm span could affect mechanical efficiency and subsequently overall race performance. Further physiological and biomechanical investigation is required on the impact of arm span on power development and race performance in BMX to validate its actual influence. If confirmed, this finding could be considered by coaches and practitioners during the talent identification process, as arm span is dependent on genetics.

5. Practical Applications.

This study has demonstrated that various factors can potentially explain BMX race performance. Our results suggest that coaches and practitioners should consider multiple characteristics when planning a training program. Namely, they should focus on short sprint power production, as this was the key component of the regression model for BMX finish time. In the current study we only discussed the final and strongest predictive model, but other variables are still important. Factors including SJ, pull strength, and VO2max could also be trained as they demonstrated a high correlation with finish time. It is apparent that individual body size could also be an important factor with a significant effect on BMX performance, and could assist the riders' selection and talent identification processes. In summary, our data presents specific aspects of BMX riders that should be targeted to maximise performance. We recommend that additional studies with more elite-level riders are undertaken to provide validity around these findings.

6. Limitations

There are several limitations which should be noted. The population of high-level BMX riders in the South Island is very limited, and including more elite level riders would increase the validity of the results. In addition to this, using more female riders in the study could provide comparative information around gender effects on BMX performance. Furthermore, using a specific BMX power meter on a real track will help to find the correlation between power produced in the lab condition and a simulated BMX race.

7. Conclusion

In conclusion, this study showed that power to weight ratio, relative BLC strength, and arm span explained 87% of the variability in BMX performance. We used a multidimensional approach to identifying contributing factors to BMX performance. This information can assist BMX coaches in prioritising specific components of training for annual periodization, as well as new riders selection process.

8. Conflict of interest

The authors report no conflict of interest.

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ORIGINAL INVESTIGATION

Determinant physiological factors of simulated BMX race

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Abstract
Evaluating the physiological demands of BMX cycling on a track provides coaches with the information required to prescribe more effective training programmes. To determine the relative importance of physiological factors during simulated BMX race, 12 male riders (age 19.2 ± 3.5 years, height 1.76 ± 0.06 m, mass 68.5 ± 4.3 kg) completed a maximum aerobic capacity ($\dot{V}O_{2max}$) test in a laboratory, and a week later, completed six laps on a BMX track interspersed by 15 min passive recovery. Peak power, immediate post-lap $\dot{V}O_{2peak}$, blood lactate, and heart rate were measured in each lap. Peak power to weight ratio was significantly correlated with lap time, however, the strength of this association decreased in each subsequent lap. Mean $\dot{V}O_{2peak}$ was greater than 80% of laboratory-measured $\dot{V}O_{2max}$ in every lap, indicating a strong contribution of the aerobic energy system during BMX racing. This study also identified that mean blood lactate was significantly associated with lap time, which showed the importance of the anaerobic energy system contribution to BMX race. Despite the short period of pedalling during BMX racing, both aerobic and anaerobic energy systems are important contributors to lap performance. Coaches should consider maximising both anaerobic power and aerobic capacity to improve riders' overall performance in multiple laps.

Keywords: *Peak power, $\dot{V}O_{2peak}$, blood lactate, cycling performance*

Highlights
- BMX is considered an intermittent sport and includes repeated high-intensity cycling sprints followed by non-pedalling periods.
- A better understanding of the physiological demands of BMX cycling on the race condition, provides coaches with data required to prescribe more effective training programs.
- The ability to repeatedly perform anaerobic efforts is an important determinant of maximal anaerobic performance.
- Oxidative metabolism can improve performance by increasing PCr resynthesize between multiple sprints.
- An effective training program should aim to enhance power to weight ratio as well as maximum aerobic capacity. Both these factors appear to affect BMX racing overall performance.

Introduction

Understanding the physio-metabolic requirements of a sport enables coaches to prescribe targeted training programmes to maximise performance. Using laboratory assessments relative to field-based workloads, researchers have identified several performance indicators in Bicycle Motocross (BMX) (Bertucci & Hourde, 2011; Daneshfar, Petersen, Miles, & Gahreman, 2020; Rylands, Roberts, & Hurst, 2015). However, laboratory measures have poor correlations with BMX race performed on a track, and this poor relationship between laboratory assessments and field performance limits the transferability of the results (Daneshfar, Petersen, Koozehchian, & Gahreman, 2020; Rylands & Roberts, 2019). Better understanding the physiological demands of BMX during a race will assist coaches to focus on the key factors that have the potential to enhance field performance.

A BMX competition usually involves qualification series, quarterfinals, semi-finals, and the final. Riders who are eliminated in the qualification series perform a minimum of three laps, while those who progress to the final complete six laps or more depending on the number of riders (Zabala et al., 2011). Each lap

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typically lasts between 30–40 s followed by 15–30 min recovery between laps, in which up to eight riders line up behind an electronic start gate awaiting the starting signal to start the next lap (Zabala et al., 2011). The start gate drops after the signal and riders pedal from a standing position down a 5–8 m ramp (UCI cycling regulations, 2019), then navigate a series of four straights with jumps separated by berms (u-bend corners).

BMX is considered an intermittent sport and includes repeated high-intensity cycling sprints (Zabala et al., 2008) followed by non-pedalling periods. The ability to perform repeated sprints is closely related to the contribution of aerobic and anaerobic energy systems (Tomlin & Wenger, 2001). Due to a significant contribution of the anaerobic energy system in high-intensity cycling sprints, a significant increase in blood lactate concentration has been reported (Zabala et al., 2011). This increase in lactic acid concentration may also lead to reduced power output and increased finish time in the latter laps.

Maintaining performance across repeated sprints requires greater ability to reduce blood lactate, regulate pH, and importantly, replenish phosphocreatine (PC) stores (Porter, Fenton, & Reed, 2019). Considering BMX racing as a repeated sprint event, data is limited regarding the relative importance of metabolic pathways and the consistency of power output over successive laps. To the authors' knowledge, only one study has examined the metabolic response of simulated BMX race with elite riders (Louis et al., 2013), and reported that high $\dot{V}O_{2peak}$ (94 ± 1% of $\dot{V}O_{2max}$) could be responsible for 54% of the variation in lap performance. This relatively high contribution is possibly due to the carryover from initial high anaerobic demands of an explosive start, technical movements, and the isometric work of the upper limbs throughout the lap. Louis et al. (2013) did not investigate the correlations between performance variables of lap time, peak power, $\dot{V}O_{2peak}$, and blood lactate. Consequently, the relationship between these factors and BMX performance remained unknown.

Currently, there is a lack of empirical data on the metabolic pathways and physiological demands of repeated BMX laps. This information will assist with the development of more effective training programmes and better monitoring of riders' progress. Accordingly, this study aimed to identify the physio-metabolic factors of BMX race in sub-elite riders. It was hypothesised that lap time would significantly correlate with the peak power output and lap $\dot{V}O_{2peak}$. Furthermore, blood lactate responses would positively associate with peak power production and post laps $\dot{V}O_{2peak}$.

Methods

Participants

Twelve nationally competitive male BMX riders participated in this study. Mean ± standard deviation (SD) of subjects' demographic data were: age 19.2 ± 3.5 years, height 1.76 ± 0.06 m, body mass 68.5 ± 4.3 kg. Subjects received written and verbal instruction regarding the risks and nature of the procedure and were asked to complete a training history questionnaire developed by the author, which identified that all had been actively involved in BMX for 5.0 ± 1.5 years. The average BMX track training time was 4.5 ± 1.5 h each week. This study was approved by the University of Canterbury's Human Ethics Committee (approval number: HEC 2018/83) and was carried out in accordance with the Declaration of Helsinki. Before commencement, all subjects completed the Physical Activity Readiness Questionnaire (PAR-Q) and provided their written consent. Parental written consent was obtained for subjects under 18 years old.

Experimental design

For testing the hypothesis, the correlations between $\dot{V}O_{2max}$, BMX lap $\dot{V}O_{2peak}$, lap time and power production were examined. To measure $\dot{V}O_{2max}$, a laboratory-based incremental intensity bike test to exhaustion was performed. This was followed a week later by simulated BMX race on a track, which included six laps interspersed by 15 min passive recoveries between each successive lap. Subjects were familiarised with the equipment and testing protocols before completing experimental testing sessions (Figure 1).

Anthropometric assessment

Stature was measured to the nearest centimetre with a wall-mounted stadiometer (Seca 213 stadiometer, Birmingham, UK) and mass was determined to within ± 0.1 kg with a digital weighing scale (Seca Quadra 808 digital scales, Birmingham, UK).

Maximum aerobic capacity ($\dot{V}O_{2max}$)

An incremental maximal cycle test was carried out on a Watt Bike Pro (Giant 2015, Nottingham, UK) which was calibrated according to the manufacturers' guidelines. The subjects performed a 6-minute warm-up at 100 W, power was then increased by 30 W per minute until volitional exhaustion occurred. The cadence and air resistance were set

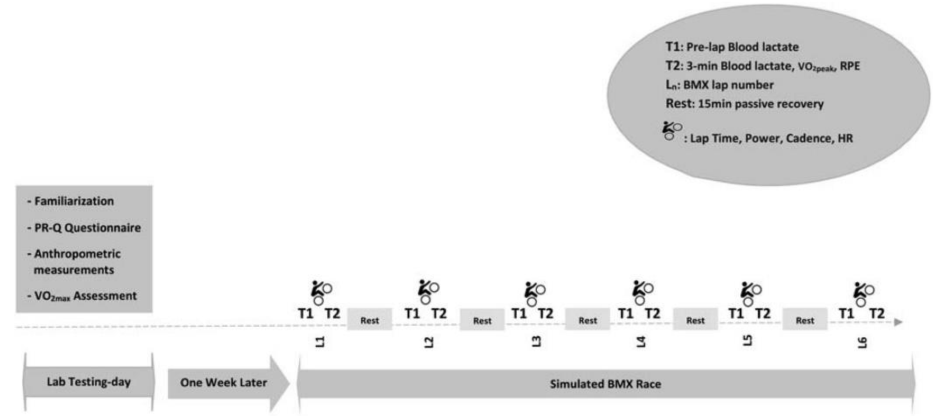

Figure 1. Simulated BMX race study design.

for each individual based on the manufacturer's guidelines for a maximal ramp test (Maximal Ramp Test, 2019). Heart rate (HR) was monitored using a GarminTM (Garmin®, Olathe, USA). Metabolic data were obtained during the test using a previously validated portable telemetric metabolimeter system Cosmed K5 (Cosmed, Rome, Italy), which was pre-calibrated following manufacturer's instructions. Before each test, the gas analyser was calibrated using a high-precision gas mixture (5.06% CO_2 and 16.02% O_2) and the spirometer with a 3-litre syringe (Hans Rudolf, Kansas City, MO, United States). Subjects were assumed to have achieved $\dot{V}O_{2max}$ if the following three criteria were met: (1) a plateau in $\dot{V}O_2$ despite an increase in power output, (2) a Respiratory Exchange Ratio (RER) above 1.1, and (3) > 90% of HR_{max} achieved during the test (Howley, Bassett, & Welch, 1995). $\dot{V}O_{2max}$ was considered to be the highest average 30 s of oxygen uptake. The peak power output was considered as the average cycling power recorded over the one minute period equating with $\dot{V}O_{2max}$ (Gastin & Lawson, 1994; Howley et al., 1995).

Simulated BMX race

The simulated race was carried out one week after the laboratory session on an outdoor track (342-meter and 28° gradient ramp), with three berms, four straights, and several technical jumps on each straight section. The simulated race was conducted in summer at a temperature of 19°C, the humidity of ~45%, and side wind speed of ~5 km/hr. Subjects were instructed to perform a warm-up to their preferences, consisting of 4–6 standing short sprints. They were then asked to complete six full laps as fast as possible from a 5-meter high start ramp using a standard electronic start gate. All subjects rode the same BMX bike (gear ratio of 43/16) fitted with a SRM BMX power meter crank (Schoberer Rad Messtechnik, Welldorf, Germany). The power meter had an eight strain gauge and a 175 mm crank arm. Prior to each test, the power meter was configured in combination with the SRM instructions. Data were downloaded using Power Control8 software (PC8DeviceAgent). To factor out the effect of body mass on power production, peak power to weight ratio (PWR) was calculated.

During the lap, HR was continuously monitored by the Garmin HR chest strap. The percentage of maximum HR obtained in the laboratory test was used for data analysis. Subjects undertook a 15-minute passive recovery between each lap as they typically undertaken in BMX race. The percentage lap time (LT) decrement (%Dec) was calculated using the following formula:

$$\%\text{Dec} = \left(\frac{(\text{LT}_{\text{mean}} - \text{LT}_{\text{best}})}{\text{LT}_{\text{best}}}\right) \times 100,$$

where LT_{mean} = mean lap time and LT_{best} = fastest lap time of the 6 BMX laps (Oliver, 2009). Lap time was measured using two sets of photocells (NEOtm Swift Performance, Queensland, Australia) positioned at the start gate and on the finish line.

Oxygen uptake

The expired gases were analysed immediately after each lap using a Cosmed K5. A mask was fitted on each subject's face covering both their nose and mouth as soon as they crossed the finish line within the first 5 s post laps. Data were recorded during the first minute of recovery. The oxygen recovery curve was measured during the first 20 s to predict peak oxygen uptake ($\dot{V}O_{2peak}$) reached during the lap (Jalab, Enea, Delpech, & Bernard, 2011; Louis et al., 2013). Afterwards, the subjects' rating of perceived exertion (RPE) was recorded using the 0–10 Borg scale ranging from very very light (0) to exhaustion (10) (Borg, 1998).

Blood lactate

Blood lactate concentration ($mmol\,L^{-1}$) was measured using a Lactate Pro2 analyser (Arkray, Kyoto, Japan), where a finger prick was commenced immediately before (baseline value) and three minutes after each lap (Tanner, Fuller, & Ross, 2010). The blood lactate response (BLr) was defined as the difference between pre-lap and post-lap lactate measures.

Statistical analyses

Before analysis, data were tested for normality using a Kolmogorov–Smirnov test and all data were normally distributed. The Statistical Package for the Social Science (SPSS 25) was used to accomplish statistical procedures (SPSS, An IBM Company, Amarouk, NY) and the results are expressed as mean ± SD. Pearson Product-Moment correlations were used to assess the relationships between $\dot{V}O_{2max}$ from the incremental test and BMX race dependent variables including lap time, peak power, blood lactate, and $\dot{V}O_{2peak}$. While dependant variables were compared between successive laps (independent variable) using a repeated-measures ANOVA. Significant main effects were further analysed by Bonferroni adjusted post-hoc test. The level of significance was set at $p \leq 0.05$ except in the instance of a Bonferroni correction in which, 0.05 was divided by the number of comparisons.

Results

The lap time was increased throughout the simulated race, showing a significant effect of lap number, where L1 was faster than L2, L3, L4, L5, L6 and L2 faster than L4, L5, L6 $F(5, 55) = 29.39$, $p = 0.004$. $\dot{V}O_{2peak}$ reached more than 80% of $\dot{V}O_{2max}$ in each lap (mean 87 ± 4% $\dot{V}O_{2max}$), but there were no significant effect of lap number on $\dot{V}O_{2peak}$ $F(5, 55) = 3.41$, $p = 0.421$. As shown in Figure 2, there was a significant effect of lap number $F(5, 55) = 22.94$, $p = 0.012$ on post-lap blood lactate values (mean = 16.4 ± 2.5 $mmol \cdot L^{-1}$).

The correlation between blood lactate and subjects' performance are presented on a scatter plot (Figure 3A). Overall, we found a significant association between mean blood lactate response (BLr) with mean lap time ($r = 0.61$; $p = 0.004$), mean PWR ($r = -0.68$; $p = 0.002$) and mean $\dot{V}O_{2peak}$ post laps ($r = -0.70$; $p = 0.001$). In addition, as presented in Figure 3B, lap time was inversely correlated with subjects' mean PWR ($r = -0.81$, $p = 0.003$) as well as mean $\dot{V}O_{2peak}$ post laps ($r = -0.72$, $p = 0.001$).

The correlations between each lap time and physiological parameters are shown in Table I. LT_{best} was significantly associated with PWR ($r = -0.70$, $p < 0.003$), $\dot{V}O_{2peak}$ ($r = -0.67$, $p < 0.005$), BLr ($r = -0.67$, $p < 0.002$) and $\dot{V}O_{2max}$ ($r = -0.76$, $p < 0.004$). LT1 and LT2 showed a similar pattern and a significant correlation with PWR, $\dot{V}O_{2peak}$, and BLr. LT3 revealed no correlation with PWR, but a significant correlation with $\dot{V}O_{2peak}$ and BLr. LT4 and LT5 were significantly correlated with PWR, $\dot{V}O_{2peak}$, BLr and $\dot{V}O_{2max}$. Going through the final stage of the race, LT6 had poor correlation with PWR, but showed significant association with $\dot{V}O_{2peak}$, BLr and $\dot{V}O_{2max}$. There was no significant correlation for RPE and HR_{max} values with race time performance.

Discussion

This study found that: (a) BMX lap time was significantly correlated with mean PWR but the strength of this association decreased as successive laps were performed; (b) Subjects demonstrated a high contribution of aerobic metabolism during laps and showed a significant correlation with mean lap times. This association indicated an incremental trend; (c) Mean BLr was significantly correlated with mean lap time, and the correlation between BLr and time in each lap was stronger in the latter laps. According to our results, despite the short (~35 s) cycling time in each BMX lap, both aerobic and anaerobic energy systems were associated with performance.

Several reports have shown that peak power is one of the most important factors related with success in BMX (Daneshfar, Petersen, Koozehchian, et al., 2020; Grigg, Haakonssen, Orr, & Keogh, 2017; Rylands, Roberts, & Hurst, 2017). In line with our results, Bertucci and Hourde (2011) reported an

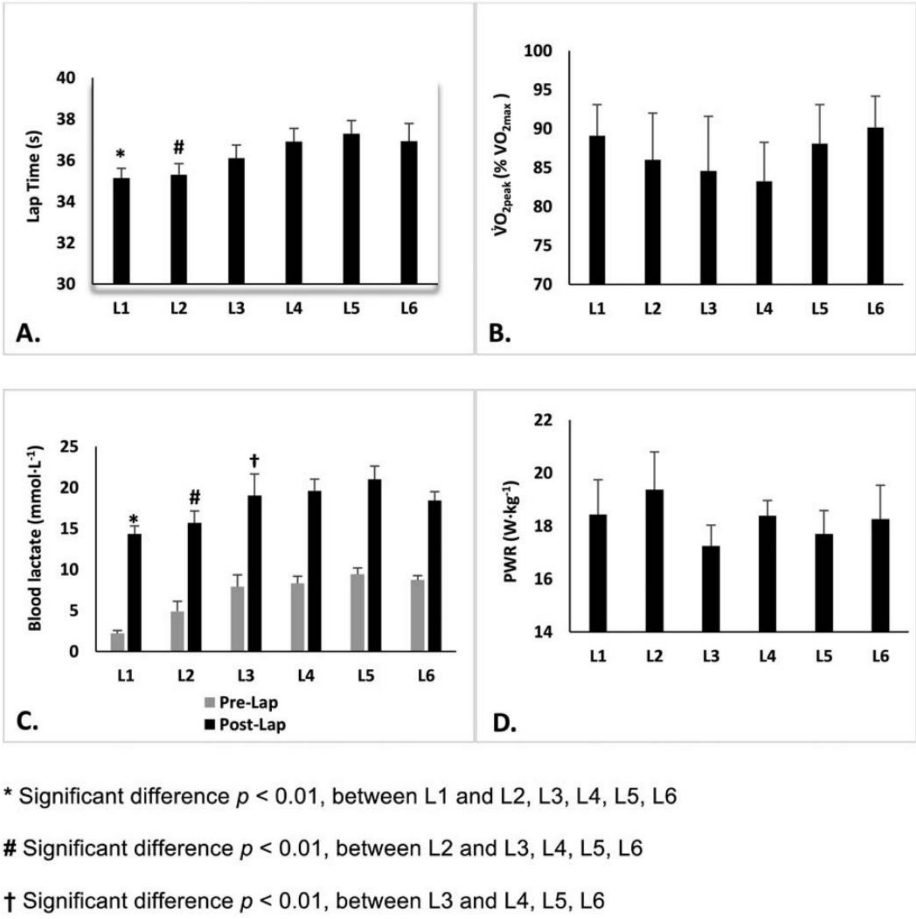

Figure 2. Simulated BMX race (Lap1–6) selected physiological components.

inverse correlation ($r = -0.67$) between PWR and sprint time in national level BMX riders over 75 m of the track (Initial Straightway).

More recently, Daneshfar, Petersen, Gahreman, and Knechtle (2020) reported that PWR of sub-elite riders 18.3 ± 2.3 $W \cdot kg^{-1}$ was significantly correlated with race time ($r = -0.68$). In the current study, PWR presented a strong correlation with the lap time ($r = -0.81$; $p = 0.003$). As the peak power occurred during the first 30 m of the track, our results were in agreement with Rylands and Roberts (2014) who concluded that riders' start performance were significantly correlated with the lap final placement. We measured riders' performance under simulated race condition, which increases the content validity and transferability of our results.

The results of the present study suggest that lap time has a significant correlation with post laps $\dot{V}O_{2peak}$ ($r = -0.72$; $p = .001$). Our results reflect those of Louis et al. (2013) who also used backward extrapolation to predict race $\dot{V}O_{2peak}$ amongst BMX riders. The authors concluded that elite BMX riders reach a very high relative $\dot{V}O_2$ during every lap (Mean $\dot{V}O_{2peak}$ $94 \pm 1\%$ of $\dot{V}O_{2max}$). A slightly lower value for mean $\dot{V}O_{2peak}$ in our study ($87 \pm 1\%$ $\dot{V}O_{2max}$), might be due to the differences in riders' aerobic capacity or their competitive level, which enabled them to perform at a greater

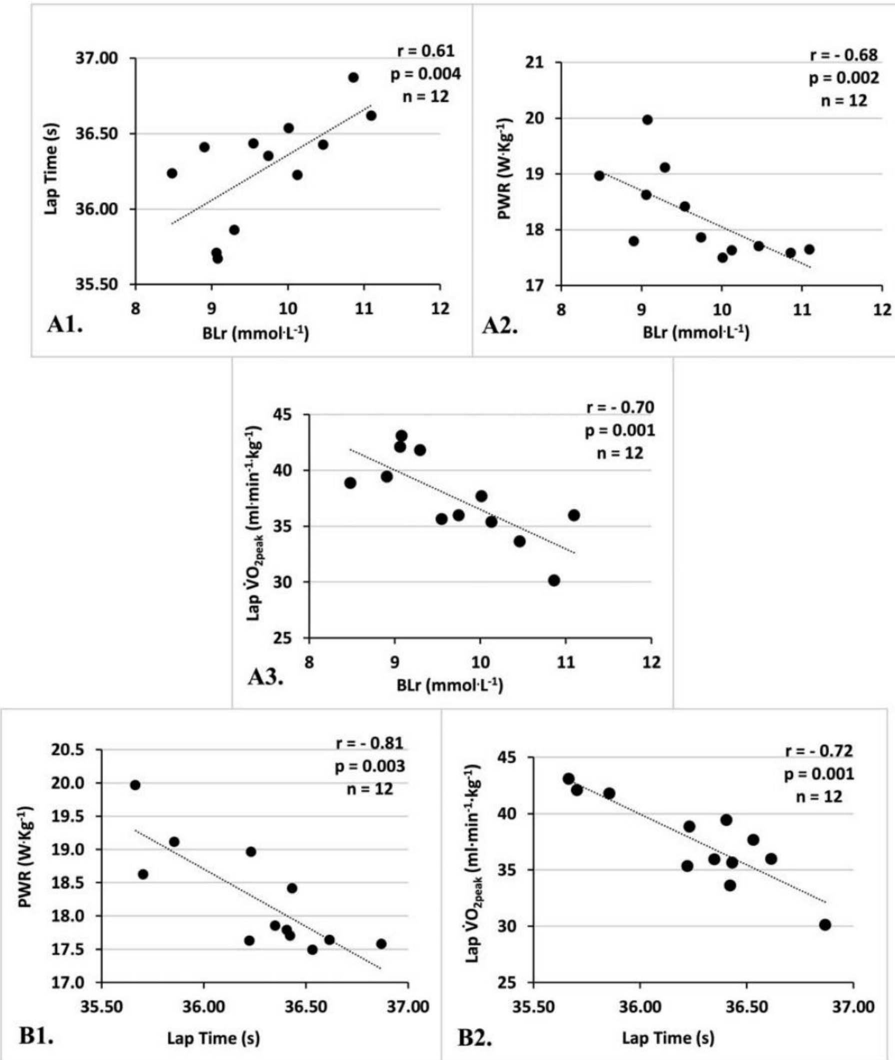

Figure 3. Scatter plot between mean BLr and (A1) mean lap time, (A2) mean PWR, and (A3) mean lap $\dot{V}O_{2peak}$. Mean lap time and (B1) mean PWR, (B2) mean lap $\dot{V}O_{2peak}$. BLr: difference blood lactate of pre and post laps, PWR: peak power to weight ratio of Lap1–6, Lap Time: finish time of Lap1–6, Lap $\dot{V}O_{2peak}$: $\dot{V}O_{2peak}$ measured post Lap1–6.

percentage of their maximum aerobic capacity. In addition, using a different tool (K4B2) and application of this equipment to measure $\dot{V}O_{2peak}$ in their study might potentially be another reason for different results. In the present study, we set out with the aim of determining the importance of metabolic pathways in BMX race performance. An incremental relationship was found between post laps $\dot{V}O_{2peak}$ with each individual lap time (R1–R6). In the earlier laps, riders' performance was more strongly associated with their anaerobic metabolism and sprint capacity; in contrast, during later

Table I. Relationship between BMX lap times with physiological variables.

	PWR	$\dot{V}O_{2peak}$	BLr	$\%HR_{max}$	RPE	$\dot{V}O_{2max}$
LT_{best}	−0.70*	−0.67*	0.67*	−0.25	0.35	−0.76**
%Dec	0.16	0.15	−0.37	0.20	−0.12	0.16
LT1	−0.70*	−0.54*	0.53*	−0.27	0.32	−0.35
LT2	−0.70*	−0.55*	0.55*	−0.02	0.45	−0.48
LT3	−0.38	−0.64*	0.56*	−0.35	0.14	−0.31
LT4	−0.60*	−0.66*	0.63*	−0.30	0.11	−0.55*
LT5	−0.53*	−0.69*	0.65*	−0.15	0.43	−0.68*
LT6	−0.38	−0.70*	0.68*	−0.09	−0.01	−0.79**

LT_{Best}: fastest time over 6 laps; %Dec: the percentage in a sprint decrement for the 6 laps; LT1–6: mean time to finish Lap1 to Lap6; PWR: mean peak power to weight ratio of 6 laps; $\dot{V}O_{2peak}$: mean $\dot{V}O_{2peak}$ of 6 laps; BLr: mean difference blood lactate of pre and post laps; % HR_{max}: mean percentage of maximum heart rate; RPE: mean rating of perceived exertion of 6 laps; $\dot{V}O_{2max}$: mean maximum aerobic capacity measured in the lab; **: correlation is significant at the 0.01 level; *: correlation is significant at the 0.05 level

laps, their performance relied on aerobic metabolism. These results are in line with other researchers who have reported significant correlations between $\dot{V}O_{2max}$ and repeated-sprint ability (RSA) performance (Bishop & Edge, 2006; Pareja-Blanco et al., 2016). In general, a more developed aerobic capacity enabled the riders to recover faster and as a result, the riders' performance declined to a lesser degree. It is worth noting that to measure post-laps VO_2, there was some delay (>5 s) from crossing the finish line to wearing the mask, therefore, the first few seconds of oxygen recovery curve might be missing and potentially influenced the VO_{2peak} values.

Our results found a high metabolic demand in a BMX race, especially in the first 10–15 s of the race, where riders generated a great power output resulting in a large rate of force development. The high metabolic demands are extended due to the continued technical work and isometric efforts of the upper body, throughout the entire lap (Rylands, Hurst, Roberts, & Graydon, 2017). In line with previous studies that have investigated the impact of aerobic metabolism on RSA, oxidative metabolism can improve performance by increasing PCr resynthesize between multiple sprints (McGawley & Bishop, 2015). These findings assist BMX coaches and riders to better understand the importance of aerobic capacity in BMX, and consider this factor when developing training programmes. Further studies should aim to re-evaluate the importance of aerobic capacity in BMX race in athletes at various levels.

In the current study, the mean blood lactate values after each lap was 16.44 ± 1 mmol L^{-1} (mean BLr = 10 ± 0.6 mmol L^{-1}). This is in agreement with those obtained by Louis et al. (2013) who reported a high blood lactate concentration (14.5 ± 4.5 mmol L^{-1}) in elite BMX riders after six laps. More recently, Petruolo, Connolly, Bosio, Induni, and Rampinini (2020) also showed that the lactate levels in elite riders reached 12.9 ± 1.6 mmol L^{-1} following four laps of simulated BMX race. The authors concluded that the performance of the subsequent lap could be affected as post-lap blood lactate values did not completely recover over 30-min rest periods. The high lactate concentration reflects high anaerobic glycolysis across the BMX laps and confirms the importance of anaerobic energy system in repeated sprints bouts. Our results also presented a strong correlation between mean BLr with lap time (Figure 3A). This may raise the assumption that subjects who have achieved better performance in their BMX lap, are those who had higher lactate concentrations post laps as a result of the greater work intensity, as well as better lactate clearance capability during the recovery. Lactate removal is an oxygen-dependent process and it is known that endurance-trained individuals have a greater ability to remove lactate following intense exercise (McLester, Green, Wickwire, & Crews, 2008). Therefore, even if aerobic fitness does not directly improve a single lap time in BMX, potentially due to greater anaerobic energy demand, it is plausible that greater oxidative capacity contributes to improved cycling performance in successive laps.

The results of the current study provide further support for the hypothesis that the ability to repeatedly perform anaerobic efforts is an important determinant of maximal anaerobic performance (McGawley & Bishop, 2015). Similar to RSA, one of the most suggested factors that may impair performance is acidosis (increased hydrogen ions H^+). Prior studies applied induced alkalosis using bicarbonate to explore ways of improving performance (Zabala et al., 2008; Zabala, Sanchez-Munoz, & Mateo, 2009), but fail to report any positive effects on riders' sprint performance. More recently Peinado et al. (2019) in a field-simulated BMX did not report any ergogenic benefit of bicarbonate on BMX performance consisting of three laps separated by 15 min of recovery. In the current study, 61% of the lap time variation was explained by BLr. To better understand the role of acidosis during BMX laps, it is essential to consider the impact of aerobic fitness and recovery approaches undertaken after laps, which are known to influence the lactate removal and acidosis level. BMX coaches should also consider sprint interval training programmes inducing high metabolic stress to improve repeated laps via greater improvements in H^+ regulation, natural buffering system, and developing aerobic capacity (Gist, Fedewa, Dishman, & Cureton, 2014; Ramos-Campo et al., 2018).

In summary, according to the results of this study, despite the short cycling time in each BMX lap, both aerobic and anaerobic energy systems showed to be associated with riders' performance. BMX coaches and practitioners may consider the importance of these factors when designing conditioning programmes. While focusing on improving riders' lap time, peak power, and technique, they should also develop riders' aerobic capacity as it plays a critical role in overall BMX performance. Sprint interval training can be a useful method for improving successive BMX laps via greater improvements in H^+ regulation, natural buffering, and developing aerobic capacity. The current approach will prove useful in expanding our understanding of how different physio-metabolic variables play roles in BMX simulated race. Future research should consider using a greater number of subjects to compare the lap demands of female and male BMX riders, as well as comparing elite and national-regional riders' performance. In addition, applying different recovery methods for BMX race and determining their effect on performance is also worthy of investigation.

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No potential conflict of interest was reported by the authors.

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ORIGINAL RESEARCH

Power Analysis of Field-Based Bicycle Motor Cross (BMX)

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Introduction: Power meter is a useful tool for monitoring cyclists' training and race performance. However, limited data are available regarding BMX racing power output. The aim of this study was to characterise the power production of BMX riders and investigate its potential role on race performance.

Methods: Fourteen male riders (age: 20.3 ± 1.5 years, height: 1.75 ± 0.05 m, mass: 70.2 ± 6.4 kg) participated in this study. The tests consist of performing two races apart from 15-min recovery. SRM power meter was used to record power and cadence. Cyclists' fastest race was used for the data analysis. Heart rate was recorded at 1-s intervals using a Garmin HR chest strap. Lap time was recorded using four pairs of photocells positioned at the start gate, bottom of the start ramp, end of first corner (time cornering), and on the finish line.

Results: There was a large correlation between race time and relative peak power ($r = -0.68$, $p < 0.01$) as well as average power with zero value excluded ($r = -0.52$, $p < 0.01$). Race time was also significantly associated with time cornering ($r = 0.58$, $p < 0.01$). Peak power (1288.7 ± 62.6 W) was reached in the first 2.34 second of the race. With zero values included, the average power was 355.8 ± 25.4 W, which was about 28% of the peak power, compared to 62% when zero values were excluded (795.6 ± 63.5 W).

Conclusion: The post-race analysis of the power data might help the cyclists recognizing the need to apply certain strategies on pedalling rates and power production in certain portions of the BMX track, specially, at the start and around the first corner. BMX coaches must consider designing training programs based on the race intensity and power output zones.

Keywords: BMX race, cadence, heart rate, power binning

Introduction

Cyclists from a recreational to elite level use power meters to examine the power output profile of training and race performance.[1] For many scientists and coaches, a simple power analysis consists of visual inspection to identify peak power and time to peak power. However, for a more thorough evaluation of power data, type of the race, track condition, and quantifying variation in power output during the race should also be considered. For instance, in some sprint cycling events such as bicycle motocross (BMX), pedalling is intermittent throughout the race; consequently, riders' power production is sporadic.

A BMX race typically lasts between 30 -50 seconds in duration. Each BMX track is unique in shape and distance and ranges between 200-400 m in length, incorporating a variety of jumps, corners, and flat sections.[2] A BMX track can be categorized into three different phases. 1) Gate start acceleration phase, which is

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determined by the gradient of the ramp and the values of maximum power production. 2) Mixed central phase, in which riders combine impulse actions without pedalling when tackling the obstacles and then, when possible, pedalling to achieve the maximum power to increase or maintain the speed already accomplished. 3) Stamina phase, in which riders try to maintain their high cyclic power output and maximum speed by pedalling and coordination, therefore, velocity stamina plays a significant role in the final performance.[3] These phases affect the BMX race technical and conditional requirements and reduce the options for applying power.

A number of studies suggest an association between peak power and BMX race performance.[4–6] These research studies mainly focused on measuring performance over the first phase of the track or short distance sprints. For instance, Rylands et al[7] were the first to use an SRM power meter system and evaluated velocity production. They compared the results of six elite BMX riders power production over a 50 m and 200 m flat asphalt surface with other cycling disciplines. Riders in this study produced peak power of 1256 ± 276 (W), which was closer to the track sprinters and more than the power outputs of the endurance mountain bike riders. A major limitation with this kind of methodology is the lack of validity and transferability of the results, as they have not undertaken their research on an actual BMX track. The same issue applies for laboratory-based measures evaluating power production.[8,9] The lab results can evaluate the capacity, but it is unknown whether this is repeatable on the track. Clearly, there is the need for a more valid method of power output measurement in BMX racing.

To the best of our knowledge to date, only Mateo et al[3] have evaluated power under a BMX race condition. Their results showed that the average peak power applied in the BMX race was 85% of the laboratory-tested maximum power. These values decreased to 73% at the gate start and to 51% on the first straight. They concluded that the power profile of elite BMX riders is dependent on certain factors, including the phases and techniques of the race, and are significantly affected by the level of track difficulty. As track characteristics influence pedalling time and require multiple technical demands, power production varies through the race. Consequently, a more detailed analysis of power output data can determine how the volume and intensity of racing (and training) has been distributed.

Power output distribution can be described within a race or training session using time spent in designated data bins or zones. Data bins are generated using percentage of total time spent within a power band. To present the data visually the bins can be plotted to produce a session histogram. Previous studies have used a data binning approach to investigate physiological responses during training and cycling competitions.[10] Ebert et al[11] used a similar comparison for two types of women's World Cup cycle road races and calculated the percentage of total race time spent within four data zones. Although simple, this method is excellent for the purpose of overall session comparisons. Due to the variable nature of the power output during BMX race, the use of data binning transposes the complex stochastic power meter data into a simple, easy to interpret output for BMX coaches.

Despite such monitoring, many BMX coaches and cyclists remain uncertain about the actual benefits of training based on power, and how to best implement the use of a power meter as a training tool. Hence, the aim of the current study was to characterise the power production of BMX riders in races. It was hypothesized that cyclists' race times would be significantly correlated with time cornering and power output of the race.

Methods

Participants

Fourteen sub-elite male BMX cyclists (age 20.3 ± 1.5 years, height 1.75 ± 0.05 m, mass 70.2 ± 6.4 kg, and training experience 6.5 ± 1.5 years) volunteered to take part in this study. Those with any recent injuries or medical conditions were excluded from the study. All cyclists were informed about the study protocol and potential risks and provided written consent by the Declaration of Helsinki. Parental written consent was obtained for subjects under-18 years old. This study was approved by the University of Canterbury's Human Ethics Committee (approval number: HEC 2018/83).

Experimental Design

Before starting the race, all cyclists' body mass (Seca Quadra 808 digital scales, Birmingham, UK) and height (Seca 213 stadiometer, Birmingham, UK) were recorded. Each cyclist then followed a structured warm-up including 5–10 standing-start cycle sprints, and dynamic stretching. After 5 minutes rest, cyclists performed two all-out BMX races from a 5-meter start ramp with a standard electronic start gate (Pro-Gate, Rockford, IL, USA). Cyclists had 15 minutes of passive recovery between races and their quickest race was used for the data analysis.

BMX Track

The track performance was described as the time taken to complete the all-out effort on a 342-meter outdoor BMX track with a 28° descent and 5-meter start ramp, four straights with several technical jumps, and three corners (Figure 1). The first straightaway is defined from where the start ramp meets the track surface till landing from the last jump. The second straightaway starts from the end of the first corner to where the rider landed from the last jump. The third straightaway is quantified as starting at the end of the second corner extending to the top of the final obstacle (small jump). The fourth and final straightaway begins as soon as the third corner is completed and extends to the finish line.[12] This track hosts BMX national competitions in the South Island of New Zealand.

Race Time Assessment

Race time was recorded using four pair of photocells (NEOtm Swift Performance, Queensland, Australia) positioned at the start gate, bottom of the start ramp, end of first corner (Time cornering), and on the finish line (Figure 2).

Power Analysis

In the current study, the SRM (Schoberer Rad Messetechnik) training system was used to measure power output during the BMX race. SRM has been shown to be a valid tool for measuring power output

Figure 1 A view of the North Avon BMX track.

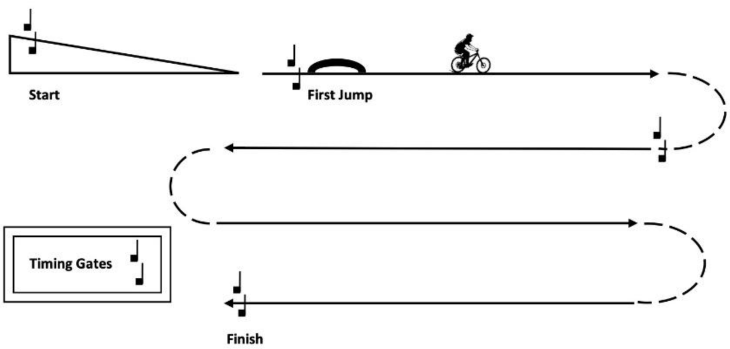

Figure 2 Schematic figure of the photocells positioning on the BMX track.

during field conditions.[13] SRM measures the power directly at the crank arm with precision strain gauges attached to the inside of a deformable disk, situated within the inner bolt circle of the crank arm. As force is applied to the cranks, the strain gauges convert this into a power value. The cadence is also assessed with every pedal revolution. This signal is then transmitted to a handlebar-mounted power controller.[13] For this test, the SRM system was set to record at 1-s intervals. Before each race, the zero offset of the power meter was re-entered into the power control unit in accordance with the manufacturer's guidelines. This offset zero was taken into account by establishing the actual output frequency of the cranks. The SRM power meter incorporated an eight-strain gauge and a 175 mm crank arm which were attached to the BMX testing bike (gear ratio of 43/16). All the relative data including peak power and cadence were downloaded after races using Power Control8 software (PC8DeviceAgent).

Binning Race Power Output

To describe the power output distribution within a race, the amount of time spent within chosen data bins was analysed. Data were then visually presented with the bins plotted as a session histogram.[11] The power bands were chosen to represent: 1) low-intensity cycling (<100 W), 2) moderate peak power (100–300 W), 3) high-intensity efforts (300–500 W) and sprints (>500 W).

Heart Rate

During the race, Heart Rate (HR) was monitored using a Garmin HR chest strap (HRM-Dual™, USA). The heart rate monitor was sampling at a rate of 1-s intervals.

Statistical Analysis

Data are presented as mean ± standard deviation (SD) and statistical significance was set at $P \leq 0.05$. All statistical analyses were conducted using SPSS 25.0 (SPSS Inc., Chicago, IL, USA). Pearson's product–moment correlation coefficient was used to determine the relationship between race variables including, race time, time to peak power, power output, cadence, and HR. During non-pedalling phase, all cyclists recorded zero values for both power and cadence. Therefore, data for average power and cadence are presented with both included and excluded zero values.

Results

There was a significant correlation between race time and relative peak power ($r = -0.68$, $p < 0.01$) as well as average power with zero value excluded ($r = -0.52$, $p < 0.01$). Race time was also significantly associated with time cornering ($r = 0.58$, $p < 0.01$). In the current study average cadence was significantly correlated with relative average power ($r = 0.68$, $p < 0.01$). There were no statistically significant associations between HR and other race variables. Mean ± SD of the race variables is presented in Table 1.

Power Output

As presented in Figure 3, power values fluctuated during the race. BMX cyclists' peak power (1288.7 ± 62.6 W) was reached in the first 2.34 second of the race. With zero values included, the average power was 355.8 ± 25.4 W which was about 28% of the peak power recorded in the race compared to 62% when zero value was excluded (795.6 ± 63.5 W). Figure 4 also showed the distribution of power production throughout the race. While non-pedalling phase contributed to ~40% of the race time, BMX cyclist generated high power (>500 W) in ~35% of the time.

Cadence

Cadence displayed a similar pattern to the power profile, as peak cadence of 131 ± 6 rev.min^{-1} occurred at 2.13s of the race. Again, with zero values excluded, the average cadence fell to 100 rev.min^{-1}. With no-pedalling periods included, the average cadence was 45 rev.min^{-1}, which equated to 22% of maximum cadence (Figure 3).

Table 1 BMX Race Variables

Variables	Mean ± SD 0-Values Excluded (0-Values Included)
Time	
Race time (s)	34.23 ± 1.21
Time to peak power (s)	2.34 ± 0.16
Time cornering (s)	12.14 ± 0.34
Power/Cadence	
Peak power (W)	1288.7 ± 62.6
Average power (W)	795.6 ± 63.5 (355.8 ± 25.4)
Relative peak power (Wkg^{-1})	18.3 ± 2.3
Relative average power (Wkg^{-1})	11.3 ± 1.4 (5.0 ± 0.9)
Peak cadence (revmin^{-1})	131 ± 6
Average cadence (revmin^{-1})	100 ± 8 (45 ± 5)
Heart rate (beatmin^{-1})	163 ± 2

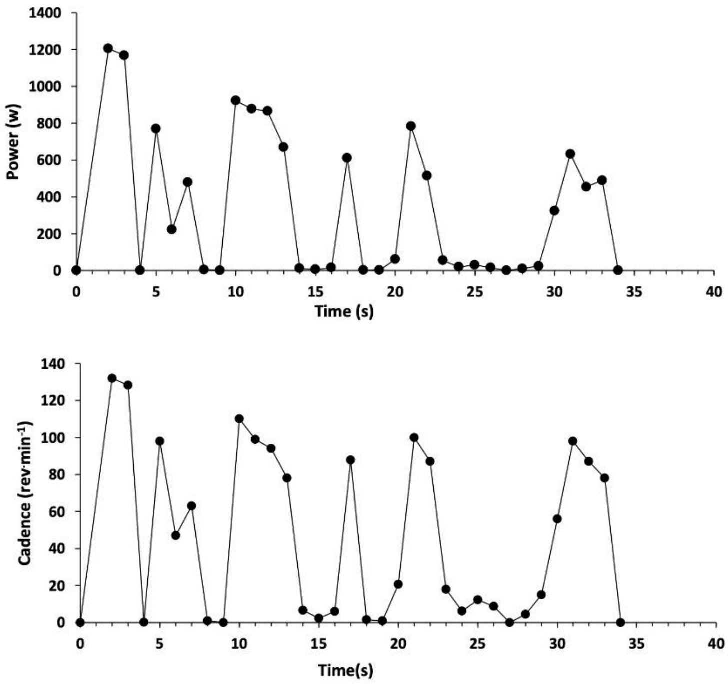

Figure 3 Mean power and cadence values recorded at 1-s intervals in the BMX race.

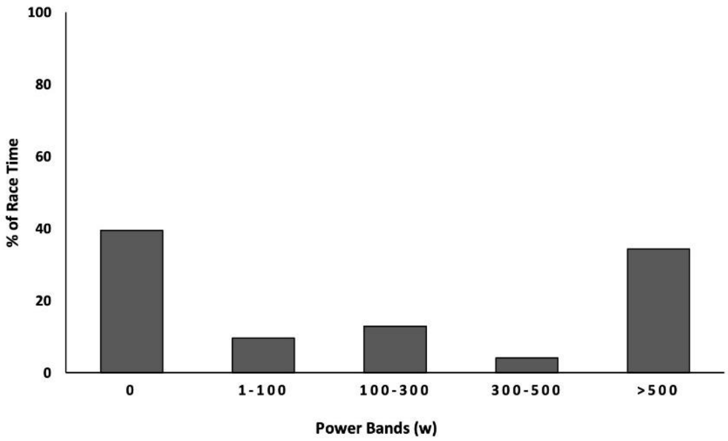

Figure 4 Power distribution in BMX race.

Herat Rate

HR reached its peak of 163 ± 2 beat.min^{-1} after 20 seconds and remained at this level for the rest of the race. As shown in Figure 5, BMX cyclists' race at ~80% of their maximum predicted HR (220-age).

Discussion

There are limited reports that have assessed BMX power performance over the range of a race. The present study was designed to analyse the power output of a BMX race and evaluate any associations between cyclists' race time and power-related variables on different parts of the track. Our results demonstrated a significant association between both peak and average power with race time, and highlighted the importance of the first straight in a BMX track and its impact on overall race performance. Furthermore, the current study provides the first report on the binning power data in BMX cycling, showing the distribution of riders' power over the race period. Time-course power analysis in the current study confirmed the previous beliefs around the intermittent nature of BMX racing.[14]

BMX cyclists in the current study reached the relative peak power of 18.3 ± 2.3 Wkg^{-1} which was significantly correlated with race time (r = −0.68, $p < 0.01$). This was in line with previous research highlighting peak power as an important determinant factor in BMX racing. Rylands et al[7] reported relative peak power of British elite male BMX riders over a 50 m flat surface 21.3 ± 0.8 Wkg^{-1}. The lower values of relative peak power are potentially due to the testing of sub-elite riders in the current study. Additionally, as Rylands et al,[7] measured performance over a flat surface and not in a BMX track, higher pedalling time would have resulted in higher power generation. Zabala et al,[8] reported peak power outputs of 1607 ± 310 W for Spanish elite BMX riders, which was 20% higher than the peak power achieved in the present study. It is worth noting that the results of Zabala and colleagues were derived from a Wingate test using a Monarck cycle ergometer, and the use of different power measuring equipment may limit transference between studies. Bertucci et al,[5] reported the peak power values (1968 ± 210 W) of the French elite riders over an 80-m field sprint and concluded that power output of the lower limb explained between 41% and 66% of the performance during the initial straightaway of BMX track. The sole study which measured power over the BMX track in three different track difficulties was conducted by Mateo et al,[3] which measured maximum power of 1343 ± 68 W in an 8-second sprint test using a Power Tap power meter among national Spanish BMX riders. Their race peak power was 1144 ± 28 W with an average time to peak power of 1.42 ± 0.02 seconds. In the current study, BMX riders reached their peak power after 2.34 seconds, but generated 12% more power in the race compared to Spanish riders. A possible explanation for these results may be the use of a different power meter, as well as testing on tracks with incompatible levels of difficulty.

Another important finding of the current study was that the average power (zero value excluded) showed a significant association (r = −0.52, $p < 0.01$) with the

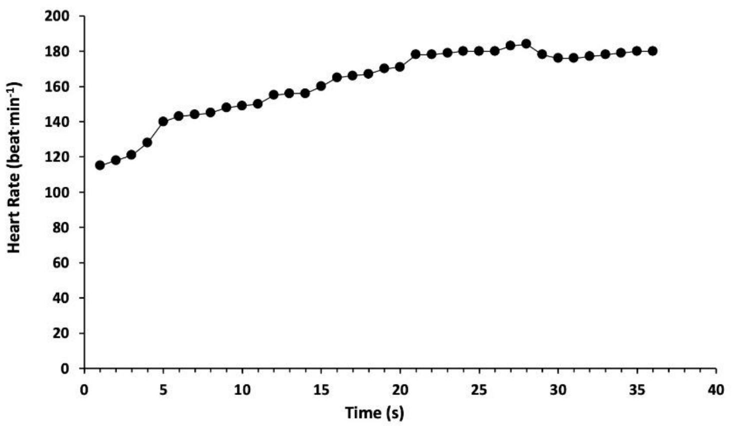

Figure 5 Mean heart rate values recorded at 1-s intervals in the BMX race.

race time. In a BMX race, pedalling is often blocked by jumps, curves, and other changes in the track, which affects the power production. However, generating power in the track corners, or when pedalling is possible, would assist riders to maintain their speed and overcome the upcoming obstacles. Therefore, besides the importance of a powerful start, and generating maximum power in the first few seconds of the race, maintaining power and velocity is another critical factor in a BMX race. There is limited data available regarding power profile of a BMX race. Only Mateo et al[3] have reported the average power of 329 ± 83 W for the entire BMX track, which was compatible with the results of current study 355 ± 25 W with zero values included. The authors indicated that on a difficult track, riders' average power dropped as there was less opportunity for pedalling and more technical sections in the race. The overall average power of a race gives insight into the actual stress imposed by a given workload, since fluctuations in power are further exaggerated by tactical considerations or track shape. Data obtained via racing with a power meter can be used to evaluate BMX performance, and consequently to evaluate the load of training and to determine what changes might need to be made to a riders' program.

Time cornering in the current study demonstrated a positive correlation with riders' overall race time ($r = 0.58$, $p < 0.01$). Our data also showed that second peak power (72% of race peak power) occurred while riders pedalled around the first corner, after an explosive power production at the start. Previous studies have highlighted the importance of the first straight in a BMX race; however, our data showed that time cornering is another important factor associated with overall race time. Cowell et al,[12] analysed the time trial event of the 2010 BMX World Championships and reported time cornering of 13.92 ± 0.42 s, while total time on the first straight was 9.16 ± 0.21 s. These authors concluded that in a BMX race, each section of the track requires a slightly different skill set and the performance on one section is likely to influence performance on subsequent sections. Based on our results, riders who had shorter time cornering were more likely to have a better overall race performance. This result may be explained by the fact that while the initial power helps BMX riders to pick up the best position in the track, their pedalling performance in the first corner can minimize any loss in speed, and provides a chance to maintain their speed by generating more power.

The present study provided a deeper analysis of BMX race power output distribution by data binning. There is a various range of power production in a BMX race. Riders spent ~35% of the race time in <500 W sprint zone which highlighted the importance of the anaerobic energy system in a BMX race. On the other hand, the non-pedalling period of a race equated for ~40% of the race time, as well as a period of producing very low power <100 W which can be considered insignificant power output. The data binning strategy has been used with road cyclists previously, where Ebert et al,[11] reported the power distribution during the Women's World Cup in road racing. Riders in their study spent ~5% of the race time in the sprint zone, where ~45% of the race time was under peak power value. One of the advantages of racing and training with a power meter is that it provides an easier way to precisely control the overall training load. By continuously recording power output, the exact demands of each race can be more accurately quantified, and the intensity or duration (or both) of subsequent training sessions can be modified. These findings help BMX riders to have a clearer understanding of power production in a BMX race and the importance of <500 W sprint zone. BMX coaches should also consider training program with high metabolic stress levels such as high-intensity interval training that could possibly improve repeated races performance.[15] Future research needs to provide data from elite riders during international BMX competitions. That would have an insight into the fitness standards required to be competitive and successful at an elite level and may offer a screening tool for coaches and sport scientists in talent identification processes.

Another finding presented in our study was the significant correlation between average cadence with relative average power ($r = 0.68$, $p < 0.01$) and this demonstrated a similar pattern to the power profile during a BMX race. Cadence has been highlighted as one of the key factors contributing to power production, and mechanical power output in cycling is dependent upon cadence.[16] However, as BMX bikes are not equipped with a gear shifter system, and riders elect to use a single-speed system, data regarding the optimal cadence and peak power is contradictory. For instance, Herman et al[17] reported that power cadence relationship could have an effect on a BMX riders' finish line placing, as the relationship occurs in the first 1.6 s of a race. Riders in this study reached peak cadence of 212 ± 4 revs.min^{-1} with peak power of 2087 ± 156 W. Debraux et al[18] analysed peak power and cadence during the 80-m sprint test and reported an optimal theoretical cadence of 122 ± 18 revs.min^{-1} that elicited peak power. In a laboratory-based study, Rylands et al[9] analysed the optimal cadence for peak power and time to peak power production, where each elite BMX rider completed three maximal sprints at a cadence of 80, 100, 120 and 140 revs. min^{-1}. These riders produced peak power (1105 ± 139 W) at 100 revs.min^{-1} and shortest time to power production were attained at 120 revs.min^{-1} in 2.5 ± 1.07 s. In the current study, riders' average cadence was 100 ± 8 rev.min^{-1}, but peak power was achieved at higher cadence (131 ± 6 rev.min^{-1}). The reason for this is that during periods when pedalling was possible, such as less technical sections or flatter areas of the track, riders appeared to generate or maintain power and velocity by relying on cadence. However, during non-pedalling phases, the majority of time was spent with the pedals static, acting more as a support platform than a dynamic performance component. Our data provided a deeper analysis on cadence and power production compared to previous studies as we measured the performance over an actual race. It is important for BMX coaches and riders to be aware of the cadence role in a race and this will provide an insight for their training intensity as well as gear selection.

The present study has several limitations. Firstly, the relatively small sample size of sub-elite BMX riders, which most likely affected our statistical power. Future studies using a larger sample size including elite BMX riders are needed to confirm these findings. Secondly, it is important to monitor BMX performance over repetitive races, which usually consists of six races in a BMX tournament, and to compare this data with other physiological variables including the aerobic and anaerobic capacity. Finally, in the current study, our power meter sampling rate was low and could potentially affect our power measurement. Using a power meter with higher sampling rate in future research would help to accurately assess field power in BMX.

Conclusions

Overall, this study strengthens the idea that power output is a critical variable in BMX race performance and should be measured over the range of the whole track under a race condition. As power is highly variable in a BMX race, the average power beside peak power provides more insight into the actual stress imposed. Therefore, BMX coaches must consider designing training programs based on the race intensity and power output zones. The post-race analysis of the power data also helps the cyclists recognize the need to apply certain strategies on pedalling rates and power production in certain portion of the BMX track. Specifically, at start of the race, time cornering and around the first corner. Furthermore, such data provide insight into cyclists' relative strengths and weaknesses. Comparison of the power profile from race to race and its association with time may indicate whether they were dropped due to accumulative fatigue if the power dropped, or would be due to the technical performance.

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Disclosure

The authors report no conflicts of interest in this work.

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ORIGINAL INVESTIGATION

The effect of 4 weeks motor imagery training on simulated BMX race performance

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ABSTRACT

This study investigated the effectiveness of a BMX specific Motor Imagery (MI) programme on simulated race performance. MI is defined as the visualisation of motor activities in the absence of physical movement and has been demonstrated to be effective for a variety of outcomes. However, to date, the transfer of MI has not been adequately evaluated in cycling specific settings. Therefore, using a crossover study, 13 sub-elite BMX riders (11 male, 2 female; age 19.2 ± 3.5 years, height 1.74 ± 0.06 m) undertook four weeks (80 min / week) MI training, in addition to normal BMX training, with a week washout between conditions. Pre and post MI training, track testing was conducted that included vertical jump and three BMX time-trials. Our data presented no significant improvement in riders' finish time following MI training in any of the three races ($p > .05$), but showed a slight improvement trend. Despite this, relative peak power significantly improved following MI practice compared to the baseline and control conditions ($p < .01$). As a BMX rider's final placing is often decided by a fraction of a second, coaches and practitioners may benefit from including MI in their training programme to improve riders' performance; however, more research is needed with different competitive levels to test this hypothesis.

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Cognitive strategy; cycling time trial; peak power; imagery ability

Introduction

Many athletes and sport coaches believe that using cognitive strategies prior to or during skill execution enhances sport performance (Slimani et al., 2016). One method that has been used extensively to improve general motor tasks is Motor Imagery (MI). MI is a form of simulation where the entire physical experience of an action (e.g., feeling, hearing, and seeing) occurs in the mind and has been shown to improve actual performance (Kosslyn et al., 2001). MI is remarkedly similar to the real sensory experience, and shares comparable mechanisms used in the actual movement preparation and even stimulates the same brain areas helping to facilitate performance (Kosslyn et al., 2001; Weinberg & Gould, 2014). As such, MI is a popular

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method utilised by sport psychologists and has attracted much research attention over the past three decades (Paravlic et al., 2018).

Yue and Cole (1992) were the first to provide evidence that MI training could improve muscular strength by 22% compared to ~4% in control group and suggested that the central programming of a voluntary contraction may have led to this improvement. Subsequently, evidence of MI benefits for enhancing muscular (the abductor digits, plantar-flexor, and distal / proximal upper extremities) strength (Ranganathan et al., 2004; Smith et al., 2003; Zijdewind et al., 2003), and muscular endurance (Lebon et al., 2010) have also been reported. Furthermore, MI has been shown to have positive effects on absolute and explosive force production, with peak ground reaction forces of an isometric pull being significantly greater when using imagery compared to no imagery (Avila et al., 2015). The above authors explained that imagery may facilitate learning of a new skill by helping the subjects rehearse and become more familiar with the actual movement. More recently, Grospretre et al. (2019) showed short-term MI training significantly improved the plantar flexors' maximal force and rate of force development, as well as resulting in greater spinal and supraspinal adaptations. These authors speculated that the various adaptive changes occurring in the brain, known as neural plasticity, could be the underlying performance-enhancing mechanism. These neural changes include the strengthening of neuronal connections, the addition or removal of connections, and new brain cell formation.

Several imagery theories exist to explain the benefits of imagery. For instance, Jeannerod (1994) argued that imagery and physical practice are functionally equivalent, and both access common neural mechanisms associated with the actual perception, motor control, and emotions of a movement. Alternatively, Lang (1979) introduced the bio-informational theory in which all knowledge is represented in memory as units of information and during imagery, individuals could access the information stored in long term memory. When required to perform the task in the future, the performer is more likely to recall the correct actions needed to produce the skill from memory. Holmes and Collins (2001) combined the bio-informational and functional equivalence theories and created the PETTLEP imagery model. In the PETTLEP model, "P" refers to the athlete's physical response to the sporting situation, "E" is the environment in which the imagery is performed, "T" is the imagined task, "T" refers to timing (or the pace at which the imagery is performed), "L" is a learning or memory component of imagery, "E" refers to the emotions elicited by the imagery and "P" refers to the visual perspective adopted by the individual. Imagery interventions based on the PETTLEP model have shown to improve complex movement and athletes motor performance in different sports, including field hockey, gymnastics routines, skiing and golf shots (Post et al., 2018). Using the components of the PETTLEP model ensures that imagery is functionally equivalent to physical practice and strengthens stimulus and response associated with the motor task.

Imagery is only beneficial when used by individuals demonstrating sufficient imagery ability (Williams, 2019), which is defined as "an individual's capability of forming vivid, controllable images and retaining them for sufficient time to effect the desired imagery rehearsal" (Morris et al., 2005, p. 20). Hall (1998) highlighted that everyone has the ability to generate an image, but this may differ in terms of vividness, controllability, kinesthetic feeling, ease, and emotion experience. Thus, imagery ability is multidimensional and can be reflected in a number of ways. In sport, the two main dimensions used to assess imagery ability are ease and vividness (Morris et al., 2005). Alongside choosing the appropriate imagery model, the effectiveness of imagery as a performance-enhancing strategy is dependent on the individual's ability to generate and control vivid images effortlessly. This is supported by Robin et al. (2007) who have demonstrated that following MI practice on tennis service return accuracy, greater improvements were experienced by those who had a better imagery ability.

Researchers recently concluded that cognitive practice benefits cyclists in both training and competition environments. This suggests long-term effects of cognitive strategies (e.g., MI) should be investigated further (Spindler et al., 2018). Cycling research to date has shown that in world-class endurance cyclists, MI appears a useful method of facilitating positive emotional states (Spindler et al., 2019). Additionally, using a mental skills package, including MI, has effectively enhanced Triathlon race performance (Thelwell & Greenlees, 2003). Potentially, MI is thought to improve pain management and endurance performance in cycling tasks by decreasing the perception of effort (Razon et al., 2014). Considering the similar effects on the brain of MI training compared to actual physical performance, it is argued that MI training could supplement physical practice and help athletes as a mental and physical preparatory tool (Cumming & Williams, 2012). Incorporating MI into training schedules could assist cycling coaches in developing riders' optimal performance in various cycling disciplines.

Bicycle Motocross (BMX) is a relatively new cycling discipline, which consists of single-lap sprint races. On a purpose-built dirt race course (~400 m), eight riders face several jumps, rollers and banked turns requiring multiple physical and technical actions to be enacted. Each race lasts 30–40 s and riders generally have a 15–30 min recovery between races, dependent upon the level of competition, with up to six races per day (Cowell et al., 2011). Previous research has investigated factors for success in BMX including physiological (muscular power, rate of power production, aerobic and anaerobic fitness level), psychological (audio-visual feedback, state anxiety), biomechanical (start position, gear ratio, cadence) and technical skills (Daneshfar et al., 2020a, 2020c; Debraux & Bertucci, 2011; Rylands et al., 2017; Zabala et al., 2009). Notably, factors such as peak power, muscular strength, and jump performance have been highlighted as the key performance indicators in BMX racing (Daneshfar et al., 2020b). In addition, Rylands and Roberts (2019) in a scoping review concluded that more multidimensional studies are required to highlight validated performance characteristics of BMX cycling, and correlation of psychological factors with BMX performance needs further investigation. In summary, despite the positive effects of MI training on muscular strength, power, recovery from fatigue and skill improvement shown in recent research (Lebon et al., 2010; Saumur & Perry, 2018; Slimani et al., 2016), the usefulness of MI practice on BMX performance remains unknown.

In sports such as BMX, specific MI involves multiple muscle groups, open chain movement patterns and motor skills. BMX coaches who are seeking to obtain performance enhancement, in particular, muscular power and motor skill learning through MI interventions, need research to establish the effects of MI practice on more complex cycling-related tasks. To the best of our knowledge, the only published use of MI with BMX riders was a recent study in which riders tried to simulate their race line positioning. In this study, total power output was found to be higher on the cycle ergometer after focusing on the environmental/emotional context from the external lane using a MI protocol (Di Rienzo et al., 2018). Given the previously highlighted findings showing the potential for MI to improve strength and power tasks, it seems plausible that MI could make a positive contribution to actual BMX race performance. Therefore, the purpose of the current study was to investigate the effectiveness of a specific MI training strategy on race performance. Based on the previous findings (Lebon et al., 2010; Saumur & Perry, 2018; Slimani et al., 2016), it is hypothesised that adding MI training to a routine track training programme will significantly improve sub-elite BMX riders' race times. In addition, riders' relative peak power will significantly increase following MI training compared with both baseline and control conditions.

Methods

Participants

We determined sample size using conservative estimates in the statistical programme G*Power 3.1 (Faul et al., 2007) for a within factor repeated measures analysis of variance (ANOVA). A total sample size of 12 riders was required to obtain a moderate effect size (Cohen's $d = 0.50$) using an alpha error probability of 0.05 and statistical power set at 0.80. The target of a moderate effect size was based on previous research exploring MI in cycling performance (Razon et al., 2014). To participate in this study, riders were recruited via advertisement within different BMX clubs and 17 riders expressed their interest. However, only 13 sub-elite BMX riders (11 male, 2 female; age 19.2 ± 3.5 years, height 1.74 ± 0.065 m, training experience 7.5 ± 2.5 years) met all the inclusion criteria and were included in this study. The inclusion criteria were that riders had more than 3 years of BMX experience with regular participation in national competitions, had no current injuries or lack of movement and had no history of cardiovascular disease, hypertension, or diabetes. The study procedures, benefits and potential risks were explained to riders and written consent was obtained. Parental signed consent was secured for those under 18 years. Riders were questioned prior to the intervention regarding their level of exposure to sport psychology and mental skills training. No rider reported having previously received any mental skills education or formal sport psychology support. The researcher provided a general introduction to MI for all riders before testing.

The experiment was conducted according to Helsinki Declaration and approved by the University of Canterbury's Ethics Committee (Ref: HEC 2018/127).

Procedures

Using a randomised, crossover trial design (Figure 1), BMX riders were ranked and pair-matched on their baseline test BMX race result and randomly allocated to undertake the MI or control condition first. When undertaking the MI condition, riders performed their mental imagery training at home in addition to their routine BMX training. When in the control condition, riders only conducted their normal BMX track training activities and were asked not to perform MI. All BMX specific training was supervised by their coach (3×1.5 h sessions per week) and followed the same intensity during the experiment. Riders trained for four weeks in both training conditions and a one-week no training washout period was employed.

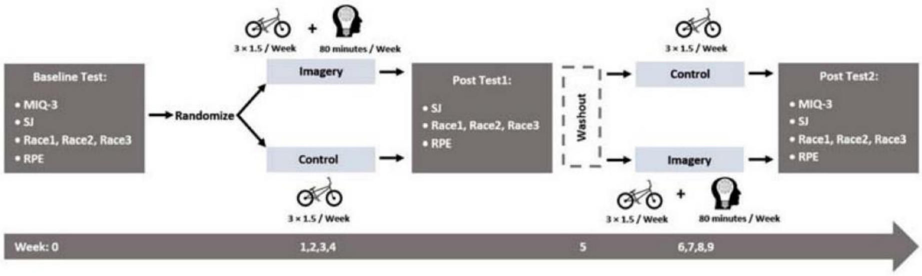

Figure 1. Motor imagery randomised cross over study design.

Race day testing

Anthropometric and vertical jump

On each test day, rider's body mass (Seca Quadra 808 digital scales, Birmingham, UK) and height (Seca 213 stadiometer, Birmingham, UK) were recorded. Each rider then followed a structured warm-up comprising 5–10 standing-start cycle sprints, then after five minutes rest, they performed a vertical jump test (Swift yardstick, Australia). The plastic vanes were adjusted according to the rider's maximum standing reach by extending their arm straight over the head (standing height). The dominant arm was closest to the vanes. Riders then performed three maximal jumps and displaced the vanes with their dominant hand, with the highest score recorded.

Power output measurement

Riders then performed three full 342 m lap races using the same BMX bike (gear ratio of 43/16) fitted with a SRM (Schoberer Rad Messtechnik Fuchsend, Germany) power meter crank. Prior to each test the power meter was configured in combination with the SRM instructions. All the relative data including peak power and cadence was downloaded after races using Power Control8 software (PC8DeviceAgent). Riders started from the top of a 5 m start ramp and a standard electronic start gate was employed.

Heart rate

During the race, heart rate (HR) was monitored by the Garmin HR chest strap (HRM-Dual™, USA). A 15-minute passive recovery was undertaken between each race.

Race time

Race time was recorded using two pairs of photocells (NEOtm Swift Performance, Queensland, Australia) positioned at the start gate and on the finish line.

Rate of perceived exertion

Rate of perceived exertion (RPE) was recorded using the 0–10 Borg scale ranging from very very light (0) to exhaustion (10) immediately after each race (Borg, 1982).

Motor imagery

Imagery ability

The Movement Imagery Questionnaire 3 (MIQ-3); (Williams et al., 2012) was used at the baseline and post-test 2 to assess the riders' ability to image movement external visual imagery (EVI), internal visual imagery (IVI), and kinesthetic imagery (KI). The MIQ-3 is a 12-item questionnaire that assesses the ease or difficulty of generating images of four different movements (i.e., knee lift, jump, arm movement, and waist bend) from an IVI perspective, an EVI perspective, and a KI modality. Participants are required to read a description of each movement, physically perform the movement, and then imagine that movement from the designated perspective. Respondents are then required to rate the resultant image on a 7-point Likert scale ranging from 1 (very hard to see/feel) to 7 (very easy to see/feel). After the items for each subscale are averaged, a higher score represents a greater ease of imaging. According to its developers, the MIQ-3 displays good internal consistency (Williams et al., 2012). Current sample demonstrated good internal reliability both at baseline and post intervention with Cronbach's alpha coefficients above 0.80 (baseline: 0.86, post-test: 0.88).

Imagery training and script

MI training included listening to a ~4-min BMX specific imagery script (2 × ~4 min MI separated by a 2 min relaxation music), which was accessed by a YouTube link (developed by researcher). Riders were asked to practice every second day, twice-a-day for four weeks at home, that totalled 80 min/week. The structure and quantity of the sessions was designed in accordance with elements of a motor imagery training session (position, location, focus, instruction type, order, eyes, perspective, mode) described by Schuster et al.'s for best practice in motor imagery (Schuster et al., 2011).

The script was aligned with the Physical, Environmental, Timing, Task, Learning, Emotion, and Perspective (PETTLEP) model (Anuar et al., 2016; Holmes & Collins, 2001). To aid in addressing the rest of the components of the PETTLEP model, an imagery script was created specifically for the BMX race in which the riders were instructed to focus on their personal thoughts and feelings related to a real BMX event. Particularly, the script addressed the task (i.e., strengthening riders' focus on their perception, feelings, and actions as they would during the physical race performance), timing (same time period as an actual BMX race), learning (focused on the "feel" of the movements as they knew how to ride and were experienced riders), and emotion (experiencing all emotions and arousal associated with performance). The physical nature of the imagery included wearing the same clothing and positioning themselves on the bike as if they were actually performing. While the environmental component ideally involves performing imagery in the physical environment that the task is actually performed in, logistically this was not possible so a photograph of the track was displayed as the background photo of the YouTube link instead. Riders were instructed to adopt and maintain their preferred visual perspective which was either EVI or IVI, throughout the MI training, whilst also incorporating the different sensations that would be experienced if physically performing the race. The script consisted of the following words:

> Find a comfortable position: standing, sitting or lying down. You are about to go through the imagery script … Warm up: Imagine a BMX Bike familiar to you. Picture the colour and shape

of the bike. You reach for the handle bar, feel the muscles in your hand and forearm flex as they grip the handle, notice the rubber of the handle …

Main Part: Imagine yourself at a race. You enter the track walking with your bike. You take your place under the shield at the start gate, listening to the gear noise and the sounds of the other riders. You notice the race official setting up the gate. Now it is your turn, imagine yourself getting ready for the race, getting into your gear, putting on your gloves and helmet. This is your best race, you are well prepared for and you feel your muscles and body ready for the race …

You get on your bike, you are behind the start gate, and you feel the wind on your face … . other riders are taking position beside you. You sit on your bike, ready for the start order. You remind yourself that you deserve a great performance the [BMX Start Order play] …

GO, GO, GO. Smash out of the gate, you are pedalling hard, the first jump, you are flying … . A smooth landing. Well done. You pump your hands, the first corner … You are pushing yourself, surging forward, digging for every last bit of energy, the last corner, smash through it. One more big push to the finish line, head down and explode across the finish line. You take of your helmet, becoming aware of the feeling of excitement and accomplishment, pride builds inside you, you have succeeded …

Manipulation check

At the end of each MI training session, riders were asked to complete a survey specifying the time and quality of their training from 1 (poor) to 7 (excellent). None of the riders reported missing any of the training sessions. Furthermore, to ensure that riders in the control condition used no imagery training, the YouTube link was removed and a control check was administered. Riders were asked to answer an open-ended question, developed by the authors, describing their daily activities. Data from the control check measure was mainly collected for controlling the experimental condition and was not subjected to statistical analysis.

Data analyses

All statistical analyses were performed using the SPSS 25 (SPSS, An IBM Company, Amarouk, NY). Data were presented in both mean and 95% Confidence Intervals (CI) and Standard Deviation (SD). A series of 3×3 repeated-measures analysis of variance; for conditions (baseline, MI, control) and time (Race1, Race2, Race3) were used to analyse race data. To analyse the vertical jump we used one-way repeated measure ANOVA. To determine changes in EVI, IVI, and KI imagery ability during the intervention, three separate 2×2 ANOVAs; for conditions (MI, control) and time (baseline, post-intervention) examined any differences between the conditions, or any changes over time. For ANOVAs involving repeated measures, the Mauchly's test of sphericity was used to test the assumptions of homogeneity of variance. When the assumption of homogeneity was violated, the Greenhouse-Geisser values were used to adjust degrees of freedom to increase the critical value of the F ratio. Statistical significance was taken at the level of ($P \leq .05$) except in the instance of a Bonferroni correction in which 0.05 was divided by the number of comparisons. Holm–Bonferroni post-hoc test was also performed to explain significant interactions. Pearson's product-moment correlation coefficient was used to determine the relationship between race performance variables and EVI, IVI, and KI imagery ability. Effect sizes were reported as partial eta-squared (η_p^2), whereby values greater than 0.01, 0.06 and 0.14 represented a small, medium and large effect, respectively (Cohen, 1988).

Results

Imagery ability

Means and standard deviation of EVI, IVI, and KI on baseline and post-test are presented in Table 1. There was no significant difference of overall imagery ability at the baseline ($p > .05$); however, riders reported significantly greater EVI, IVI and KI post intervention. Results for EVI indicated a significant effect of time, $F(2, 24) = 25.32$, $p = .020$, $\eta_p^2 = 0.55$, but no main effect of condition $F(1.55, 12.13) = 1.89$, $p = .421$, $\eta_p^2 = 0.03$ or interaction of condition and time $F(1.13, 14.12) = 1.21$, $p = .162$, $\eta_p^2 = 0.08$. There was also a significant effect of time for IVI and KI (IVI: $F(2, 24) = 23.15$, $p = .001$, $\eta_p^2 = 0.65$; KI: $F(2, 24) = 27.22$, $p = .001$, $\eta_p^2 = 0.71$). While the results showed no significant effect of condition (IVI: $F(1.57, 10.32) = 18.25$, $p = .251$, $\eta_p^2 = 0.08$; KI: $F(1.45, 12.11) = 21.08$, $p = .231$, $\eta_p^2 = 0.09$) or interaction of condition and time (IVI: $F(1.21, 11.02) = 19.15$, $p = .525$, $\eta_p^2 = 0.11$; KI: $F(1.25, 10.18) = 25.03$, $p = .141$, $\eta_p^2 = 0.06$) for IVI and KI. Post hoc analysis revealed that both the MI and control conditions improved their EVI (MI: $p = .003$; control: $p = .011$), IVI (MI: $p = .002$; control: $p = .013$) and KI (MI: $p = .005$; control: $p = .001$) imagery ability from before to after the intervention.

Furthermore, our results found no significant correlation between MIQ-3 subscales and race finish time (EVI: $r = 0.26$; $p = 0.92$, IVI: $r = 0.32$; $p = 0.57$, KI: $r = 0.28$; $p = 0.21$) or relative peak power (EVI: $r = 0.16$; $p = 0.24$, IVI: $r = 0.32$; $p = 0.24$, KI: $r = 0.18$; $p = 0.41$).

During the training weeks, the self-estimated imagery survey (mean: 5.8 ± 1.3 out of 7) did not show any significant fluctuation from one day to another $F(2.12, 25.11) = 1.25$, $p = .345$, $\eta_p^2 = 0.09$.

Race finish time

The results showed no statistically significant interaction of condition and time for the race time $F(2.17, 26.10) = 1.38$, $p = .267$, $\eta_p^2 = 0.10$. Despite that, there was an improvement trend of 2.4%, 0.6%, and 0.8% in MI condition compared to baseline for Race1, Race2 and Race3, respectively.

There was no statistically significant condition effect $F(1.40, 16.74) = 0.82$, $p = .451$, $\eta_p^2 = 0.06$ or time effect $F(2, 24) = 1.41$, $p = .263$, $\eta_p^2 = 0.10$ on time to finish (Table 2).

Relative peak power

As presented in (Table 2), there was a significant condition effect $F(2, 24) = 25.59$, $p = .001$, $\eta_p^2 = 0.68$ of MI which resulted in a significant increase in relative peak power when compared to baseline and control condition ($p < .001$). Furthermore, there was a significant time effect on relative peak power where the values in Race1 were significantly greater than Race2 $F(2, 24) = 3.58$, $p = .004$, $\eta_p^2 = 0.23$. However, the interaction of condition and time was not significant for relative peak power $F(2.53, 30.40) = 1.52$, $p = .230$, $\eta_p^2 = 0.11$.

Table 1. Mean ± SD of movement imagery questionnaire-3 scores.

	Baseline	MI	Control
MIQ-3 sub-scales			
EVI	4.23 ± 1.21	4.85 ± 0.98*	4.65 ± 1.03*
IVI	4.37 ± 1.35	4.78 ± 0.92*	4.70 ± 0.95*
KIN	4.22 ± 1.26	4.60 ± 1.10*	4.51 ± 0.99*

Notes: EVI: external visual imagery, IVI: internal visual imagery, and KI: kinesthetic imagery.
*Significantly greater than Baseline ($p < .01$).

The results of cadence at peak power failed to present any statistically significant difference of time and condition $F(1.43, 12.25) = 2.12$, $p = .344$, $\eta_p^2 = 0.12$ and $F(2.52, 20.28) = 5.52$, $p = .144$, $\eta_p^2 = 0.22$, respectively.

Vertical jump, heart rate, and RPE

There were no statistically significant effect of condition $F(2, 24) = 0.79$, $p = .467$, $\eta_p^2 = 0.06$ or time $F(2, 24) = 0.32$, $p = .162$, $\eta_p^2 = 0.10$ for vertical jump. In addition, current results for HR and RPE showed no statistically significant effect of time (HR: $F(2, 24) = 21.25$, $p = .141$, $\eta_p^2 = 0.05$; RPE: $F(2, 24) = 20.12$, $p = .321$, $\eta_p^2 = 0.02$), or condition (HR: $F(2, 24) = 25.11$, $p = .091$, $\eta_p^2 = 0.21$; RPE: $F(2, 24) = 19.12$, $p = .241$, $\eta_p^2 = 0.11$) (Table 3).

Discussion

The aim of this study was to assess whether using a BMX specific MI training would improve riders' performance. In particular, the effectiveness of MI on power measures and time trial performance was investigated. The main finding of our study revealed that four weeks of MI training did not significantly improve riders' race time, yet we did find a significant improvement in riders' power production within the first and third races. There was no significant difference in riders' imagery ability at the baseline and their ability improved equally across conditions. While many studies have investigated the efficacy of MI as a cognitive strategy, to our knowledge, this is the first study to use MI practice alongside routine track training in BMX riders. To simplify the practical applicability of the current study and descriptive utility, we have included both effect

Table 2. Mean ± SD of race finish time and power output.

	Baseline	MI	Control
Race Finish Time (s)			
Race1	36.00 ± 1.34	35.15 ± 1.44	36.13 ± 1.33
Race2	36.22 ± 1.67	36.02 ± 1.57	36.05 ± 1.55
Race3	36.34 ± 1.56	36.04 ± 1.30	36.51 ± 1.55
Peak Power (W)			
Race1	1271 ± 148	1312 ± 145	1277 ± 143
Race2	1305 ± 179	1215 ± 199*	1290 ± 175
Race3	1265 ± 169	1280 ± 152	1246 ± 166
Relative Peak Power (W kg^{-1})			
Race1	18.1 ± 2.1	18.8 ± 2.3†	18.2 ± 2.1
Race2	18.6 ± 2.4	18.5 ± 5.7*	18.4 ± 2.3
Race3	18.0 ± 2.5	18.3 ± 2.2	17.8 ± 2.4

†Significant difference ($p < .01$) between MI and both Baseline and Control condition.
*Significant difference ($p < .01$) between Race1 and Race2.

Table 3. Race data mean with 95% CI.

Race1		Race2	Race3	Average
Cadence at Peak power (rev min^{-1})				
Baseline	137 [131.2–143.2]	130 [124.3–136.0]	135 [129.7–141.3]	134 [130.8–137.7]
Control	137 [131.8–142.5]	132 [127.9–135.9]	136 [132.8–140.3]	135 [132.3–138.2]
Heart Rate (beats min^{-1})				
Baseline	174 [168–181]	182 [178–186]	181 [177–186]	179 [175–182]
MI	179 [176–183]	183 [181–186]	183 [180–186]	182 [180–183]
Control	176 [173–182]	183 [180–186]	181 [176–185]	180 [176–183]
RPE (0–10)				
Baseline	8.5 [7.4–9.3]	8.6 [7.5–9.7]	8.5 [7.4–9.5]	8.2 [8.3–9.6]
MI	8.8 [7.7–9.8]	9.4 [8.3–9.6]	9.7 [8.5–10.0]	9.3 [8.3–9.7]
Control	8.6 [7.2–9.7]	9.5 [8.3–10.0]	9.5 [8.2–10.0]	9.4 [8.4–9.7]
Vertical Jump (cm)				
Baseline	48.5 [42.3–52.8]			
MI	50.2 [44.7–53.0]			
Control	50.8 [44.8–53.9]			
Mass (kg)				
Baseline	70.4 [67.1–73.7]			
MI	69.8 [66.6–73.0]			
Control	70.3 [67.1–73.5]			

sizes and confidence intervals. Despite the importance of statistical significance, in studies with a small sample size, consideration of the magnitude of effect is often more sensible for the interpretation of the results (Rhea, 2004).

MI practice has been used as a substitute or supplementary training programme to preserve muscle function when athletes are not being exposed to maximal training intensities (Paravlic et al., 2018). In addition, Cumming and Hall (2002) suggested that imagery can be considered deliberate practice where highly structured and purposeful practice is applied to improve performance. As indicated in Table 2, race time did not improve statistically following MI practice across three races. Despite this, there appears to be a trend of faster race time for riders in the MI condition. In the first race, riders finished the race 2.4% and 4% faster than the baseline and control condition, respectively. In a BMX race, competition is generally very close and any minor improvement in finish time, relative to other competing riders, can significantly affect final placing. Therefore, BMX coaches and researchers are always trying to find ways to improve the race time and general performance. For instance, Rylands et al. (2017) ascertained that optimal cadence selection could result in a 1.0 s decrease in time of power production. Similar to the current study, their results were not statistically significant but the authors concluded (based on a publicly accessible database during the 2012 World Cup Supercross Series) that these improvements could affect a riders' final placing between 1st and 4th position. In our study, four weeks of MI training, in addition to routine BMX training, improved riders' average time by 1.44 s, which was not statistically significant. However, this change may have a real influence on riders' final ranking.

The second main finding of our study was a large ~4% improvement in relative peak power in the first race compared to the baseline and control condition. Riders in MI condition also reached ~3% more relative peak power in Race1 compared to Race2. In the current study, producing higher power following MI training was similar to previous research that showed MI can improve strength and power. For instance, Saumur and Perry (2018) indicated that three weeks of MI training may have the potential to improve quadriceps strength by 10%. Ranganathan et al. (2004) demonstrated a 35%

increase in elbow flexion strength after MI in young healthy individuals. Similar findings have also been reported by Lebon et al. (2010) who identified a 26% increase in the maximal concentric strength and eight additional repetitions for the leg press after MI training. Yue and Cole (1992) have also reported that MI may significantly increase muscle twitch force. There are possible explanations for why current MI interventions theoretically could provide an effective tool for BMX coaches and riders.

Firstly, it is supported that neurological adaptation after mental practice are similar to those elicited by physical practice (Paludo et al., 2017), and this can be obtained with a short period of MI training, which might improve coordination and enhance the muscle fibre recruitment. Secondly, cognitive components of the MI script, which refer to the imagery of race strategies, could lead to higher confidence and decreased anxiety levels (Lebon et al., 2010; Slimani et al., 2016). Therefore, MI might have contributed to improve peak power by enhancing riders' motivation and self-confidence, or regulating the anxiety related to a competition. Future research can assess the effectiveness of MI training on motivation and anxiety level and validate this among BMX riders. Finally, the PETTLEP model utilised in designing the imagery script, maximised the functional equivalence by ensuring that the imagery performed is a close representation of the actual BMX race performance. This is in line with previous reports showing the PETTLEP-style imagery is effective to improve muscular strength (Smith et al., 2003; Wakefield & Smith, 2009; Wakefield & Smith, 2011) and sport performance (Smith et al., 2007; Wakefield & Smith, 2009). In addition, as the largest performance effects would be seen when MI is completed frequently (Wakefield & Smith, 2011), riders in the current study were practicing MI twice a day/ three times a week. Thus, this design is in accordance with the notion of deliberate imagery practice (Cumming & Hall, 2002), and other findings also showed that a greater frequency of imagery produced greater improvement in performance (Wakefield & Smith, 2009; Wakefield & Smith, 2011).

It is worth noting that we did not identify any changes on vertical jump performance, which was used to monitor potential changes on riders' muscular power after using MI protocol. Our results supported the specificity of race MI script, as BMX riders were using MI to simulate the race performance and not the vertical jump. Our data also showed no significant effect of MI training on riders' HR and RPE which were considered as control variables to monitor riders' physiological response during the race. Presenting similar HR and RPE levels across conditions provides evidence that all riders experienced similar physical load during effort expenditure. While Razon et al. (2014), reported that using MI could assist endurance cycling task by decreasing RPE, our data supported those studies that failed to identify any differences in RPE during physical performance (Connolly & Janelle, 2003; Razon et al., 2010).

In the current study, imagery ability improved equally across conditions. This supports previous findings that MI practice can improve imagery ability (Cumming & Ste-Marie, 2001; Williams et al., 2013a). As having a better imagery ability can significantly influence the MI effects, we measured this variable pre and post intervention. Our results found no association between improved imagery ability with riders' race performance. This might be due to the method (self-reported questionnaire) being used to measure imagery ability, instead of using a combination of qualitative, psychometric, chronometric, and psychophysiological approaches (Collet et al., 2011). In contrast to current finding, Vergeer and Roberts (2006) found a positive correlation between imagery vividness, measured throughout the intervention, and improvement in movement flexibility. Williams et al. (2013a) showed improving imagery ability resulted in an enhancement in motor performance of a golf putting task. Their results revealed, following MI practice, individuals with lower imagery ability can experience improvements in being able to see images in two days and being able to feel the images in three days. Riders in the current study had no previous experience of MI training and demonstrated no differences in baseline imagery ability. This was the first study to determine the effects of MI on BMX race performance. Our results were somewhat conflicting, on the one hand, there were improvements in power production, but on the other, the trend of improved race times did not reach the threshold for statistical significance. It can be argued that while power is believed to be a key performance indicator in a BMX race, there are apparently other factors influencing riders' finish time. For instance, in a BMX race, and especially in the third and fourth straightway, technical skill and riding coordination can significantly affect performance (Cowell et al., 2011, 2012; Philippe Campillo, 2007). However, in the current study, we did not measure riders' skill execution; it is possible that the improved power production coincided with a decrease in skill execution, thereby offering an explanation for the lack of significant improvement in race time. Skill execution is therefore an important area for future studies to consider when assessing the effect of MI training on BMX riders' skill development. As MI did not decrease performance, it is likely to be a safe addition to BMX training programmes and supplement normal training. Emphatically, as MI can be a genuine learning approach (Cumming & Williams, 2012; Paravlic et al., 2018), coaches can use MI training as an alternative tool for teaching new techniques or while training young riders. Elite riders may respond differently to the current study and further research should be undertaken to ascertain if MI can improve elite race performance when combined with physical training. Future research should also try to identify the effectiveness of MI intervention for improving movement technique across a range of skill types for both elite and sub-elite riders. Research should explore the optimal method for delivering MI intervention, for example, using different scripts or establishing the effect of imagery on a particular part of the BMX race such as the start or technical sections.

It is important to point out several possible limitations associated with the experiment. Firstly, the 2 × ~4 min MI practice applied in the current study might have been too long as riders had no previous experience with imagery and this potentially affected the quality of the imagery sessions. Furthermore, as there are no agreed evidence-based guidance for dose–response of imagery interventions, further research is required to validate the optimal length of MI script. In addition, 45% of the current script was race preparatory phase, which is similar to sport imagery, and 55% was the main race section of motor imagery. Future work must consider investigating the optimal combination of sport imagery and motor imagery when developing the script. The content of the current script was not personalised or semi-personalised, and was fixed during the training. We assumed that consistency of the MI might help riders to familiarise better with the script. Furthermore, we only apply a one-week washout period in the crossover design due to the riders' availability and annual competition schedule. Future research may look at applying more personalised scripts, as well as a longer washout period to avoid any carry-over effect of MI training. In addition, as individuals may experience different physiological responses to MI training and riders in the current study practiced MI at home; it was hard to monitor their physiological characteristics during or after training. Therefore, future studies, may look into having a supervised training and monitor HR, or electromyography to determine the muscular response to the MI training and compare these with the physical training in the BMX race. Another limitation of the current study was that the manipulation check did not provide insight regarding imagery quality in detail (e.g., visual perspective, ease of generating, vividness, controllability). Reporting the quality of MI session was not an established dimension and perhaps too broad to understand the riders' experiences throughout the intervention. Hence, to understand the individual experiences of the riders during MI training, more precise measurement of imagery quality is required (Williams et al., 2013b). The environmental component ideally involves performing imagery in the physical environment that the task is actually performed in; logistically this was not possible so a photograph of the track was used instead. It is proposed that more vivid imagery may occur when an individual holds a relevant piece of sporting equipment (Anuar et al., 2016), however we did not ask riders to sit on their bike while imagining. Therefore, the script is not entirely consistent with PETTLEP model. Future studies should apply MI training while entirely following PETTLEP model (Wakefield et al., 2013) and consider practicing at the BMX track prior to each race or on separate days. Finally, the small sample size potentially affected the current study outcomes. In the current study we applied MI training among 13 sub-elite BMX riders. Elite riders with a higher technical and physiological level may respond differently to the MI training. Future research should recruit more riders and consider using elite level riders to validate our findings.

Conclusion

In conclusion, this study provides initial evidence that combining 4 weeks of MI training programme with BMX practice does not significantly affect riders' race time, but could improve peak power production. Improved muscular power in the current study following MI training supported the application of MI as a supplementary training method beside physical practice to enhance athletic performance. Particularly, this information might be of interest to BMX coaches and riders themselves, who would like to add mental practice in their annual training programme. Athletes should also be encouraged to incorporate the PETTELEP model into their imagery as much as possible to achieve more effective results. In addition, imagery ability improved across both conditions in all three sub-scales (EVI, IVI, KI), however, current results failed to show any significant correlation between imagery ability and riders' race time and relative power. Future research might look to explore the effect of MI training and use alternative measures to understand the role of this cognitive strategy in sport performance.

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Human Kinetics
ORIGINAL RESEARCH

Caffeinated Chewing Gum Improves Bicycle Motocross Time-Trial Performance

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This study aimed to identify the acute effects of caffeinated chewing gum (CAF) on bicycle motocross (BMX) time-trial (TT) performance. In a randomized, placebo-controlled, double-blind cross-over design, 14 male BMX riders (age = 20.0 ± 3.3 years; height = 1.78 ± 0.04 m; body mass = 72 ± 4 kg), consumed either (300 mg; 4.2 ± 0.2 mg/kg) caffeinated (300 mg caffeine, 6 g sugars) or a placebo (0 mg caffeine, 0 g sugars) gum, and undertook three BMX TTs. Repeated-measure analysis revealed that CAF has a large ergogenic effect on TT time, $F(1, 14) = 33.570$, $p = .001$, $\eta_p^2 = .71$; −1.5% ± 0.4 compared with the placebo. Peak power and maximal power to weight ratio also increased significantly compared with the placebo condition, $F(1, 14) = 54.666$, $p = .001$, $\eta_p^2 = .79$; +3.5% ± 0.6, and $F(1, 14) = 57.399$, $p = .001$, $\eta_p^2 = .80$; +3% ± 0.3, respectively. Rating of perceived exertion was significantly lower $F(1, 14) = 25.020$, $p = .001$, $\eta_p^2 = .64$ in CAF (6.6 ± 1.3) compared with the placebo (7.2 ± 1.7). Administering a moderate dose (300 mg) of CAF could improve TT time by enhancing power and reducing the perception of exertion. BMX coaches and riders may consider consuming CAF before a BMX race to improve performance and reduce rating of perceived exertion.

Keywords: caffeine, power output, sprint cycling

Research demonstrates anaerobic performance can improve following caffeine supplementation (Stojanović et al., 2019). Proposed mechanisms include increasing neurotransmitter release and motor unit firing rates (Kalmar, 2005), enhancing muscle contractility as a result of altered calcium kinetics and/or sensitivity (Allen & Westerblad, 1995), and decreasing perception of effort related to adenosine receptor antagonism (Davis et al., 2003). A recent meta-analysis demonstrated caffeine might induce meaningful improvements in power and upper body muscular strength (Grgic et al., 2018). Acute improvement in vertical jump height following a single caffeine ingestion has reported roughly equivalent to 4 weeks of plyometric training (Grgic et al., 2018; Markovic, 2007); however, other studies have reported no improvements in anaerobic performance following caffeine consumption (Anderson et al., 2018; Polito et al., 2016). Given various methodological consideration including dose; consumption method (capsules/pills, drink, and chewing gum); and testing procedures (Goods et al., 2017), the effects of caffeine on short-duration high-intensity performances are equivocal.

Chewing gum was first used by the military to rapidly restore alertness and performance and is an alternate form of caffeine administration (Wickham & Spriet, 2018). Effective absorption of caffeine via gum occurs primarily through buccal mucosa within 5–10 min of administration, compared with 20–30 min with capsule ingestion, although total caffeine absorption over time is not different (Syed et al., 2005; Wickham & Spriet, 2018). Previous studies have used caffeine doses ranging from 100 to 300 mg, administered 5–10 min preexercise. Venier et al. (2019) reported up to 4.5% improvement in vertical jump and power in resistance-trained men after consuming 300 mg caffeinated chewing gum (CAF). Paton et al. (2010) administered 240 mg of CAF to competitive cyclists who completed four sets of five 30 s maximal sprints with 30 s of active recovery between each set. Their results showed that the rate of dropped power output in sets 3 and 4 was significantly reduced after CAF versus placebo. Similarly, Ryan et al. (2013) observed enhanced cycling time trial (TT) after delivering 300 mg of caffeine via chewing gum 5 min before exercise. Interestingly, the same dosage 60 and 120 min preexercise failed to show any ergogenic effects. Therefore, CAF may prove beneficial where athletes are required to provide a quick increase in repeated anaerobic performance, such as in bicycle motocross (BMX) racing.

The BMX racing is a mass-start bicycle event where riders race entirely in a standing position. A race typically lasts 35–45 s and takes place on a 300 to 400 m track. Riders generally complete up to six races on a competition day with 15–30 min recovery between races (Cowell et al., 2012). Multiple physiological factors contribute to the success of a rider include explosive start, time to peak power, and anaerobic muscular power (Daneshfar et al., 2020b; Debraux & William, 2011). BMX is considered an intermittent sprint cycling sport, and researchers continue to investigate ways to improve performance (Daneshfar et al., 2020a; Rylands & Roberts, 2019).

If caffeine enhances short-duration, high-intensity performance by increasing anaerobic power and sprint speed, then

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BMX riders may benefit from the consumption of CAF. No previous study has investigated the benefits of caffeine administration on BMX performance. This study aimed to determine the acute effects of CAF on BMX TT performance. It was hypothesized that CAF would improve TT time and power production.

Methods

Experimental Design

In a randomized, placebo-controlled, double-blind, cross-over design, the effects of consuming CAF were assessed on TT time as the primary outcome. Power output, blood lactate (BL), heart rate (HR), and rating of perceived exertion (RPE) were also measured as possible mechanistic factors responsible for changes in TT time. After familiarization, data were collected on two additional occasions (CAF trial and placebo trial), interspersed with 1-week washout period. This study was conducted during the competitive phase of the BMX season, and all trials took place between 5 and 7 p.m. to control for diurnal variation (Figure 1). The study was carried out according to the Declaration of Helsinki and approved by the University of Canterbury's Ethics Committee.

Participants

Riders for the study were recruited via advertisement within BMX clubs, and 16 riders expressed interest. Only 14 male riders, who compete regionally and train four sessions per week, (age = 20 ± 3.3 years; height = 1.78 ± 0.04 m; body mass = 72 ±4 kg; BMX experience = 6.5 ± 2 years) met all the inclusion criteria and were included in the study. Riders needed to be 16–35 years, not a regular caffeine consumer, have any allergies to caffeine, and have no current injuries or movement restrictions. All riders were informed of the purpose and risks associated with participation before giving their written consent. Parental consent was obtained for riders under 18 years of age. To calculate study power, a conservative estimate in the statistical program G*Power (version 3.1; Heinrich Heine Universität Düsseldorf, Düsseldorf, Germany; Faul et al., 2007) for a within-factor repeated-measures analysis of variance was performed. This analysis suggested a minimum of 12 riders to obtain a moderate effect size (Cohen's $d = 0.50$) based on research examining effects of CAF on sprint cycling (Paton et al., 2010), an alpha error probability of .05, and statistical power of 0.90.

Dietary and Food Control

To identify any caffeinated products that riders regularly consumed, they were provided with a list of common caffeinated products including beverages, food, medicines, and supplements prior to participating in the study. A 3-day food diary analysis showed average daily caffeine consumption was ~52.8 ± 40.0 mg, which is classified as low caffeine users (Paton et al., 2010). Riders were instructed to follow an identical diet, abstain from caffeine, and any vigorous physical activity 24 hr prior to the familiarization trial, and replicate for subsequent trials.

Experimental Trial

Riders first performed a familiarization trial, followed by two additional trials separated by a 1-week washout period. In the familiarization trial, height and mass were measured; then, after 10 min standard warm-up, riders performed three BMX TTs interspersed with 15 min passive recovery. TTs were conducted on a 342 m outdoor BMX track with a 28° descent, 5 m high start ramp, four straights with several technical jumps on each straight section, and three corners. On completion of the familiarization trial, an independent academic, who was not an investigator in this study, randomized the order in which riders would complete two other trials, using a random sequence generator (GraphPad Software, San Diego, CA). On the two additional trials, riders' weight was measured, and they completed similar BMX TTs with either CAF or a placebo administered. The TTs were conducted in summer at temperatures of 19–25 °C, humidity of 40–45%, and wind speed of ~5–8 km/hr (Metservice, 2020).

CAF Administration

Caffeine was administered as an absolute dose of three pieces (300 mg; 4.2 ± 0.2 mg/kg body mass) of a commercially available gum (Military Energy Gum, Chicago, IL), with each stick providing 100 mg of caffeine and 2 g of sugars. The placebo was a similar looking and tasting (0 mg caffeine, 0 g sugars), commercially available gum (Spearmint Extra, NSW, Australia). In order to aid blind delivery, gums were divided into small pieces and placed in a container. The effectiveness of blinding was explored following the method by Saunders et al. (2017). In this study, we asked the riders before and after each TT which type of gum they had consumed. The three-scale response included: (a) caffeinated gum, (b) placebo gum, and (c) I do not know. In both experimental conditions

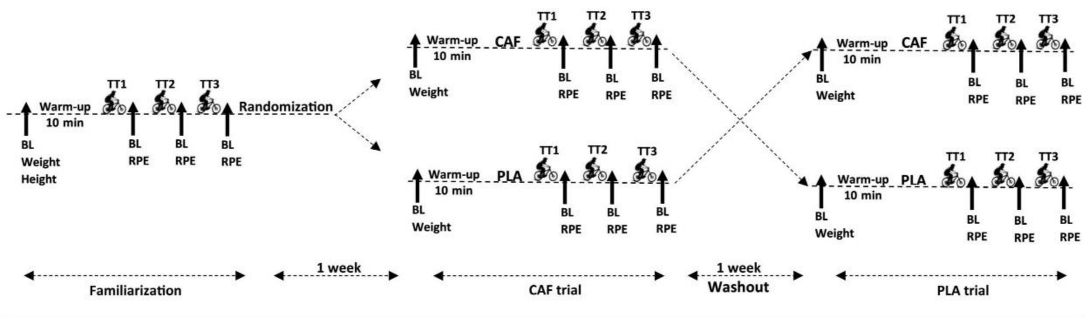

Figure 1 — Overview of the experimental design. TT_n = Time Trial 1, 2, and 3; BL = blood lactate; RPE = rating of perceived exertion; CAF = caffeinated chewing gum; PLA = placebo chewing gum.

(caffeine and placebo), the gums were chewed for 10 min before TTs (Venier et al., 2019), then expectorated into a container.

Performance Measures

The performance measures (dependent variables) included TT time, absolute peak power, maximal power to weight ratio (MPW), time to peak power, cadence at peak power, BL, HR, and post TT RPE. To record TT time, two pairs of photocells (NEOtm Swift Performance, QLD, Australia) were positioned at the start gate and on the finish line. BL concentration (mmol/L) was measured using a Lactate Pro2 analyzer (ARKRAY, Inc., Koyoto, Japan). A finger prick was taken before warm-up and 3 min post each TT (Tanner et al., 2010). To record RPE, riders rated "how hard was that TT" on a CR-10 Borg scale immediately following each TT. The RPE represented a recall of their feeling during the TT that they had just completed (Borg, 1982; Foster et al., 2001). This method was introduced to riders in the familiarization trial and was replicated for the additional trials. A Garmin HR chest strap (HRM-Dual™, Olathe, KS) was used to monitor HR during TTs.

The power output was measured using a Schoberer Rad Messtechnik (SRM) power meter, which incorporates an eight strain gauge and 175-mm crank arm. This was attached to the BMX testing bike (gear ratio of 43/16) used by all riders. SRM has shown to be a valid tool for measuring power output during field conditions (Gardner et al., 2004). All the relative power output data were downloaded using Power Control8 software (PC8DeviceAgent, Jülich, Germany; http://www.srm.de/products/software/). Relative maximal power to riders' weight was also calculated and presented as MPW (in watts per kilogram).

Statistical Analysis

Statistical analyses were performed using SPSS (version 25.0; IBM Corp., Armonk, NY). Data are presented as mean ± *SD* and an alpha level of $p \leq .05$ was considered statistically significant. A series of 2 × 3 repeated-measures analysis of variance for conditions (CAF and placebo) and time (TT1, TT2, and TT3) were used to analyze data. With repeated measures, when analysis of variance interactions were significant, adjusted Bonferroni post hoc tests were also performed. Effect sizes were reported as partial eta-squared (η_p^2), with values of <.10, .10–.24, .25–.39, and ≥.40 considered trivial, small, moderate, and large effect sizes, respectively (Cohen, 1992). A coefficient of variation (CV) was calculated using data collected during familiarization TTs and placebo TTs to study the day-to-day variation of the performance variables. To explore the effectiveness of blinding, the Bang's Blinding Index was utilized. The blinding index was scaled to an interval of −1 to 1, with 1 indicating complete lack of blinding, 0 being consistent with perfect blinding, and −1 indicating opposite guessing. Blinding data were reported as a percentage of individuals who identified the correct condition beyond chance.

Results

Body Mass

There was no significant difference in riders' body mass $F(2, 28) = 3.452$, $p = .451$, $\eta_p^2 = .19$ in CAF trial (72.4 ± 3.0 kg) compared with placebo trial (72.2 ± 6.2 kg).

Time-Trial Time

There was a significant condition effect on TT time $F(1, 14) = 33.570$, $p = .001$, $\eta_p^2 = .71$; −1.5% ± 0.4 following CAF consumption compared with placebo. There was no significant interaction of Condition × Time, $F(1.65, 23.16) = 0.105$, $p = .866$, $\eta_p^2 = .01$, on TT time (Figure 2).

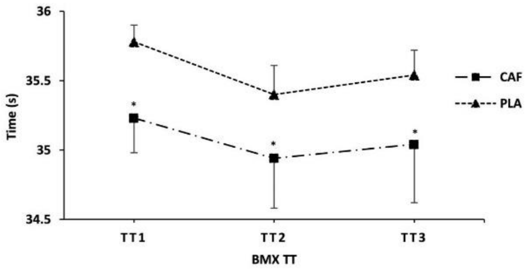

Figure 2 — Mean ± *SD* of the BMX performance time over three TTs. CAF = caffeinated chewing gum; PLA = placebo chewing gum; TT = time trial. *Significant main effect of condition $p < .001$, indicating that riders completed each TT faster following CAF compared with PLA.

Power Output

Peak power. A significant condition effect was observed for peak power, $F(1, 14) = 54.666$, $p = .001$, $\eta_p^2 = .79$, and riders in the CAF condition generated more power compared with placebo +3.5% ± 0.6. There was no significant interaction of Condition × Time, $F(2, 28) = 3.420$, $p = .082$, $\eta_p^2 = .14$, on riders' peak power.

Maximal power to weight ratio. Consuming CAF influenced riders' MPW, $F(1, 14) = 57.399$, $p = .001$, $\eta_p^2 = .80$, with values in the CAF condition being 3% ± 0.3 greater than placebo (Figure 3). There was no significant interaction of Condition × Time, $F(2, 28) = 3.512$, $p = .088$, $\eta_p^2 = .13$, on riders' MPW.

Time to peak power. There was no significant interaction of Condition × Time, $F(2, 28) = 0.621$, $p = .411$, $\eta_p^2 = .10$, nor condition effect, $F(1, 14) = 1.890$, $p = .124$, $\eta_p^2 = .14$, on riders' time to peak power (Figure 4).

Cadence. The authors' data demonstrated no significant main effect of condition, $F(1, 14) = 2.542$, $p = .133$, $\eta_p^2 = .15$, on cadence at peak power. There was no significant interaction of Condition × Time, $F(2, 28) = 3.310$, $p = .098$, $\eta_p^2 = .19$, on riders' cadence.

Heart Rate

There was no significant effect of CAF on riders' HR during the TT, $F(1, 14) = 1.472$, $p = .245$, $\eta_p^2 = .09$, as well as no significant interaction of Condition × Time, $F(2, 28) = 2.415$, $p = .108$, $\eta_p^2 = .12$ (Table 1).

Rating of Perceived Exertion

The RPE values significantly reduced, $F(1, 14) = 25.020$, $p = .001$, $\eta_p^2 = .64$, in CAF condition (6.6 ± 1.3) compared with the placebo (7.2 ± 1.7). There was no significant interaction of Condition × Time, $F(2, 28) = 1.437$, $p = .322$, $\eta_p^2 = .10$, over TTs (Table 1).

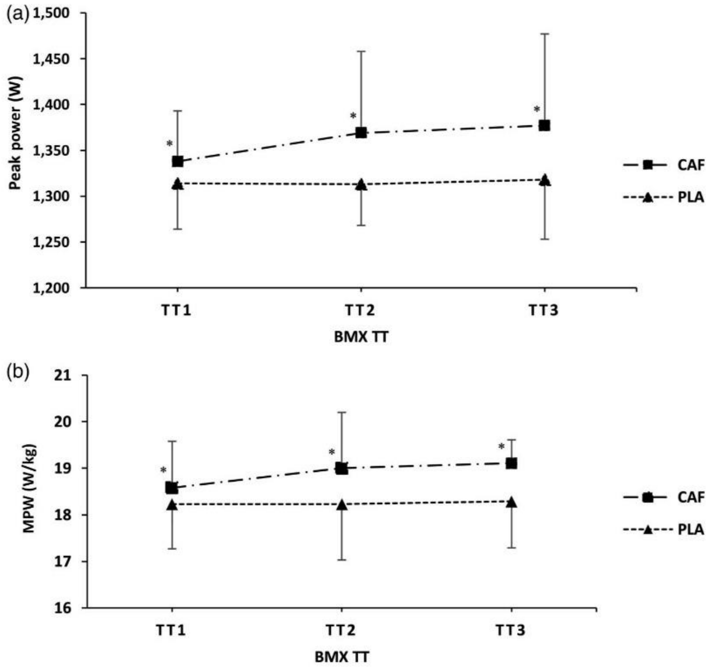

Figure 3 — Mean ± *SD* of (a) peak power and (b) MPW over three TTs. CAF = caffeinated chewing gum; PLA = placebo; TT = time trial; MPW = maximal power to weight ratio. *Significant main effect of condition $p < .001$, CAF more than PLA.

Blood Lactate

There was a significant effect of time on riders' BL values, $F(2, 28) = 457.191$, $p = .001$, $\eta_p^2 = .97$; however, no significant interaction of condition was observed, $F(1, 14) = 2.404$, $p = .143$, $\eta_p^2 = .15$ (Table 1).

Coefficient of Variation

The day-to-day variation of TT variables was shown in Table 2.

Blinding Evaluation

Before starting the TTs, 44% of riders in the placebo and 56% in the CAF condition correctly guessed the content of the chewing gum. While after TTs, 27% and 59% of riders in the placebo and caffeine conditions correctly identified the gum type, respectively, whereas 14% of riders declared they did not know what they had consumed.

Discussion

Caffeine's effects on short-term high-intensity activities are inconclusive (Cordingley et al., 2016). This study set out with the aim of identifying the effects of CAF administration on BMX riders' TT performance. The authors' findings indicated that 300 mg; 4.2 ± 0.2 mg/kg caffeine delivered via chewing gum improved TT time, absolute power, and MPW with riders demonstrating lower RPE. To date, a few studies have identified the effects of CAF on sporting performances (Dittrich et al., 2019; Paton et al., 2015; Ranchordas et al., 2019; Russell et al., 2020); however, to the best of the authors' knowledge, this is the first to investigate caffeine intake on BMX TT performance.

Compared with placebo, CAF significantly improved TT time by 1.5%. A BMX race is generally very close, and the variation of time is marginal. Based on analysis of the 2012 World Cup Supercross Series by Rylands and Roberts (2014), mean deviation in final positioning between first and second place was 0.13–0.85 s, and from first to third place was 0.38–1.52 s. In the current study, administering CAF resulted in a 0.50 s improvement in time, which could influence the final positioning in a BMX race. However, as riders' day-to-day variation for TT time were 1.2%, despite demonstrating a large effect size, the improved TT time following caffeine condition was close to the day-to-day variation. The authors calculated the day-to-day variation using data collected under different conditions (familiarization and placebo), which might affect the reliability of CV. Future research might need to consider having separate baseline measurements to analyze the precise CV and provide further details on the role of CAF on BMX TT time.

In the current study, a moderate dose of CAF improved riders' absolute power by +3.5% with a large effect size. This magnitude was in line with Paton et al. (2015), who reported ~4% enhancement in sprint power output during a laboratory simulated, 10-km cycling trial, following approximately 3–4 mg/kg caffeine administration.

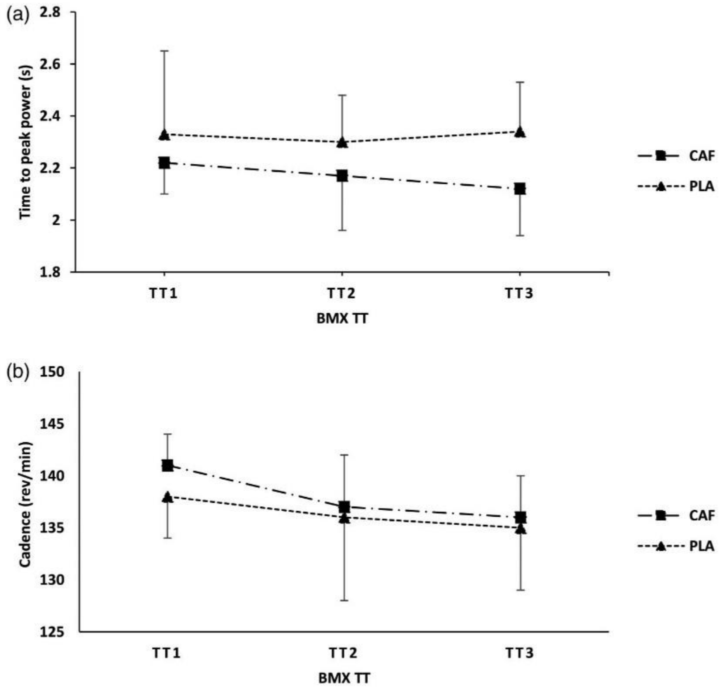

Figure 4 — Mean ± *SD* of (a) time to peak power production and (b) cadence at maximum power over three TTs. CAF = caffeinated chewing gum; PLA = placebo; TT = time trial.

Table 1 Heart Rate, RPE, and Blood Lactate Over Three BMX TTs

		BMX TTs		
TT variables	**Condition**	**TT1**	**TT2**	**TT3**
Heart rate (beats/min)	CAF	176 ± 5	182 ± 4	186 ± 2
	PLA	175 ± 3	183 ± 3	183 ± 3
RPE (1–10)	CAF	6.5 ± 1.3*	6.5 ± 1.0*	6.7 ± 1.8*
	PLA	6.9 ± 2.0	7.1 ± 1.2	7.3 ± 1.2
Blood lactate (mmol/L)	CAF	10.4 ± 2.3**	14.1 ± 2.6	16.3 ± 2.1
	PLA	10.3 ± 1.4**	13.9 ± 1.2	16.2 ± 1.8

Note. Values are presented as mean (*SD*). RPE = rating of perceived exertion; TT = time trial; CAF = caffeinated chewing gum; PLA = placebo chewing gum. *Significant main effect of condition $p < .001$, CAF lower than PLA. **Significant effect of time $p < .001$, TT1 compared with TT2 and TT3.

Table 2 Test–Retest Reliability of the BMX TT Measurement

TT variables	Average CV (%)
Time (s)	1.2
Power (W)	1.5
MPW (W/kg)	1.5
Cadence (rev/min)	1.6
Blood lactate (mmol/L)	1.8
Heart rate (beats/min)	2.1
RPE (1–10)	1.7

Note. RPE = rating of perceived exertion; TT = time trial; CAF = caffeinated chewing gum; PLA = placebo chewing gum; MPW = maximal power to weight ratio.

Paton et al. (2010) also showed ~6% improvement in repeated 30 s sprint performance in male competitive cyclists who consumed 240 mg caffeine by chewing gum. In another experiment, Ryan et al. (2013) showed that a dose of 3 mg/kg caffeine delivered 5 min precycling by gum in trained cyclists, improved 7-kJ/kg TT cycling performance. Consuming CAF in the current study helped BMX riders to produce ~40 W greater peak power in TT3 compared with TT1. Increasing power production can significantly influence BMX riders' race performance (Daneshfar et al., 2020a). Specifically, at the start of the race, where gaining the front position would significantly affect the overall results (Rylands & Roberts, 2014). As chewing gum appears to be an effective and quicker method of caffeine ingestion for athletes compared with pills/capsules, administration by this method may be particularly advantageous for BMX riders prior to racing or during recovery time.

Anaerobic power output relative to body weight (power to weight ratio) is a popular measure of ability among competitive cyclists (Lunn et al., 2009). Similar to peak power, the authors found CAF improved riders' MPW up to 3% compared with placebo. These findings are contrary to a recent study by Anderson et al. (2018), who reported no positive effects of consuming (250 mg, 3–6 mg/kg) caffeine on anaerobic power, even though five out of nine cyclists exhibited an increase in Wingate peak power during the caffeine trial. The results of the current study are in line with Woolf et al. (2008), who demonstrated ~5% improvement in MPW of Wingate test following 5 mg/kg caffeine consumption in 18 highly trained men. Therefore, the authors' study, in addition to Woolf et al.'s (2008) study, supports the ergogenic effects of CAF on cycling anaerobic power.

The BL concentration showed a significant increase from 10 mmol/L in TT1 to 16 mmol/L in the TT3, which supports the highly anaerobic nature of BMX racing (Louis et al., 2013). While CAF has no ergogenic effects on BL, these findings seem to be consistent with other researchers who reported no significant effect of caffeine on BL (Anderson et al., 2018; Glaister et al., 2012; Greer et al., 1998; Hahn et al., 2018). In contrast, a number of studies have found a significant increase in BL following caffeine ingestion in both trained and untrained subjects (Anselme et al., 1992; Carr et al., 2008; Cordingley et al., 2016; Woolf et al., 2008). Further research is required to establish the effects of caffeine on BL during BMX TTs. While the authors' data showed a main effect of time on HR over TTs, there was no significant effect of CAF on riders' HR. It was expected an increased HR response in CAF condition as caffeine directly reduces the parasympathetic nervous system activity (Sondermeijer et al., 2002), but in higher exercise intensities, this difference tends to disappear as the sympathetic nervous system dominantly controls HR (Karapetian et al., 2012). The findings of the current study support those who reported no ergogenic effects of CAF on HR (Ryan et al., 2013; Woolf et al., 2008).

Another mechanism by which caffeine improves performance is a reduction in perception of effort (Davis et al., 2003). It is believed caffeine works as an adenosine antagonist and hence delays fatigue and improves alertness and mood (Astorino & Roberson, 2010; Hahn et al., 2018). Stuart et al. (2005) reported the ergogenic effect became more apparent in the latter half of repeated tests. Caffeine also lowers peripheral fatigue and RPE (Sökmen et al., 2008) and provides a greater capacity to tolerate the discomfort associated with tiredness during exercise (Doherty & Smith, 2005). This is supported by data in the present study, whereby CAF decreased riders' RPE levels with a large effect size. The authors' findings are in agreement with researchers who reported the ergogenic benefits of caffeine on RPE (Doherty & Smith, 2005; Doherty et al., 2004; Glaister & Gissane, 2018; Greenland et al., 2019). The authors' data provided an insight for those competitive BMX riders who have low habitual caffeine consumption and who are interested in consuming caffeine prior to training and racing to improve their performance. Future research should be undertaken to validate these findings, using elite or riders who are habitual caffeine consumers.

In the current study, all subjects received the same dosage of 300 mg of caffeine, and this corresponded to a range of 3.8–4.4 mg/kg. The authors did not measure blood caffeine concentrations; therefore, the amount of caffeine absorption in the blood with different doses of caffeine remains unclear. Also, absorbed sugar from CAF in oral cavity could potentially affect performance by activating brain regions related to the sense of reward and pleasure, similar to the mechanism involved in improved performance following carbohydrate mouth rinse (de Ataide e Silva et al., 2013; Ferreira et al., 2018). Furthermore, CAF and placebo gums contained a variety of other different ingredients (e.g., artificial colors and flavors) that may have affected the study outcomes. Future research should use chewing gum with identical contents to avoid the influence of additional substances. In addition, despite the effective blinding method, given the greater importance of the pre-TT responses compared with the post-TT responses, the percentage of riders who correctly identified the placebo beyond chance pre-TT (44%) was greater compared with post-TT (14%). Also, the authors did not measure exercise-induced pain after TTs, and the effects of CAF on riders' perception of pain remained unclear. Despite providing instruction for riders' diet, the authors did not control their diet and hydration during the trials which may have affected the study outcomes and is therefore a limitation of the present study. It is worth noticing that based on Foster et al. (2001) study to collect retrospective recall RPE; subjects would rate the Borg CR-10 scale 30 min after experiment. The authors asked riders to rate their feeling immediately following TTs, which could affect the validity of the RPE results. Finally, to measure performance, riders performed TTs using the same BMX bike with a fixed gear ratio. As riders typically use their personal bike and compete with others in a race, this might affect the power production and their overall performance.

This is the first study to explore the effects of CAF on BMX performance. The authors' novel findings demonstrated that CAF containing 300 mg caffeine and 6 g of sugar versus noncaffeinated sugar-free placebo gum improved TT time, boosted riders' power up to 3%, and decreased their post-TT RPE. It may be appropriate to consume the current caffeine amount 10 min prior to a BMX race to improve performance by enhancing power production and reducing perception of exertion, particularly where successive races are required.

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13 Appendix 3 Journal Publication During PhD, Not Related to the Thesis

Mehdi Gheitasi, Mohammad Bayattork, Lars Louis Andersen, Saeed Imani, **Amin Daneshfar**. **Effect of twelve weeks pilates training on functional balance of male patients with multiple sclerosis: Randomized controlled trial.** Journal of Bodywork and Movement Therapies, Volume 25, 2021, Pages 41-45. ISSN 1360-8592
https://doi.org/10.1016/j.jbmt.2020.11.003
https://www.sciencedirect.com/science/article/pii/S1360859220302187

Iran Red Crescent Med J. 2018 February; 20(2):e13305. doi: 10.5812/ircmj.13305.

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The Effect of Aerobic Training on Tumor Growth, Adiponectin, Leptin and Ghrelin in Mice Models of Breast Cancer

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Abstract

Background: Breast cancer is widespread in Iran and exercise training is an adjuvant strategy for managing this illness.
Objectives: The aim of this study was to investigate the effects of aerobic training on tumor growth and its relationship with changes in adiponectin, leptin, and ghrelin in mice with breast cancer.
Materials and Methods: In this animal experimental study, which was conducted during year 2016 in Iran, 20 female BALB/c mice were randomly divided to two groups: Tumor Control (TC) and Exercise (E). The MC4L2 cancer cells were injected in the mice. The E group then performed progressive aerobic training for six weeks. Tumor volume, food intake, weight, and muscle endurance of all mice were measured weekly. At six weeks, the mice were sacrificed and tumor, gastrocnemius muscle, and heart weights were measured. Level of cytokines/hormones were quantified using the Enzyme Linked Immunosorbent Assay (ELISA) methodology in tumor, serum, muscle, and adipose tissue.
Results: Aerobic exercise training was associated with a significantly decreased growth rate and final weight of the tumor (1.11 versus 2.74 g) compared to the TC group ($P < 0.05$). Exercising mice also had greater food intake, muscle endurance, heart weight (0.12 versus 0.09 g), and muscle weight (0.078 versus 0.045 mg) when compared with the TC group ($P < 0.05$). In addition, the E group had significantly increased adiponectin in all sites except the tumor, decreased leptin in all sites, and increased ghrelin in serum compared to the TC group ($P < 0.05$).
Conclusions: Aerobic exercise training in mice with breast cancer attenuated tumor burden and cachexia, and improved appetite, muscle size and function and fitness relative to non-exercising controls.

Keywords: Adipokine, Breast Cancer, Cachexia, Ghrelin

1. Background

Cancer cachexia is defined by an ongoing loss of skeletal muscle mass with or without loss of fat mass, associated with progressive functional impairment. Loss of muscle mass leads to lower strength, which in turn leads to decreased mobility and quality of life and increases mortality by 25% to 30% in patients with cancer (1). Since cachexia is a multifactorial syndrome, effective treatment strategies must be multifaceted as well; there is some evidence that regular physical activity by itself can be an effective therapeutic strategy for cancer cachexia (2, 3). Cachexia is characterized by a negative protein and energy balance driven by a variable combination of reduced food intake and abnormally high metabolism (4). Food intake and metabolism are regulated by hormones, neuropeptides, and cytokines, including, ghrelin, leptin, and adiponectin (5). These cytokines, which are involved in the regulation of feeding, may play an important role in both general and cancer cachexia (6).

Ghrelin, a 28-amino acid peptide, is produced in the stomach, stimulates food intake and growth hormone secretion, suppresses inflammation, reduces energy expenditure, and attenuates muscle catabolism (7). These functions suggest that ghrelin could improve cachexia. In this regard, it has been shown that ghrelin injection in mice with cancer (8) led to increased food intake and body weight and improved cachexia compared to control mice. Another way to increase endogenous ghrelin levels appears to be via modulation of physical activity levels. For example, ghrelin levels in the circulation increased following moderate-intensity aerobic training in healthy adults (9). However, there are no studies investigating the effect of exercise training on ghrelin levels in animal or human models of cancer (including mice with breast cancer).

Leptin, an adipocytokine secreted mainly by adipose tissue, acts to suppress food intake and stimulate energy expenditure (5), and plays an important role in breast cancer development through a variety of pathways. Li et al. (2016) showed that leptin significantly increased tumor volume, lung metastases, and tumor-associated macrophage markers in xenograft tumor-bearing mouse models (10). Del mar Blanquer et al. (2016) showed a role for leptin in metabolic reprogramming (i.e. an enhanced use of glucose for biosynthesis and lipids for energy production). Unlike most normal tissues, cancer cells tend to "ferment" glucose into lactate even in the presence of sufficient oxygen to support mitochondrial oxidative phosphorylation (the Warburg effect). The metabolic adaptations induced by leptin may enhance Michigan Cancer Foundation-7 (MCF-7) tumor growth and may underlie the reverse Warburg effect (11). Notably, energy expenditure through exercise, independent of energy intake, may beneficially modulate leptin levels. For example, four weeks of aerobic training that lowers adiposity has been shown to concomitantly reduce circulating leptin concentrations in obese individuals (12). Aerobic exercise has been shown to be an effective adjuvant therapy in females with breast cancer, yet the role of leptin modulation in these benefits is largely unknown, as there is limited evidence to date assessing the effects of exercise on leptin levels within tumor tissue, adipose tissue and/or circulation in either animal models or human patients with cancer.

Adiponectin (also known as ACRP30) is another member of the adipocytokine family, which may be important in cancer prognosis. It is induced during adipocyte differentiation, and its secretion is stimulated by insulin and Insulin-like Growth Factor-1 (IGF-1). Like leptin, adiponectin is involved in metabolism and inflammation yet in a reverse manner (5). Adiponectin serum levels are inversely associated with body weight, adiposity, and inflammation. Thus, low adiponectin levels are found in obesity and metabolic syndrome (13), and high levels are found in anorexia nervosa (14) and during weight loss (15). However, results are heterogeneous in cancer-related adiposity and weight changes in cancer cohorts. For example, reduced levels of serum adiponectin have been reported in patients with breast cancer (16) compared to healthy controls. However, in another study, no correlation was observed between weight loss and adiponectin levels in patients with breast and colon cancer (6). Finally, in another report, in contrast to increased adiponectin, generally observed after weight loss in healthy individuals, adiponectin levels decreased after weight-loss in advanced lung cancer (17). Exercise can also modulate leptin and adiponectin levels in healthy adults and animals (18). Most commonly, higher adiponectin has been associated with higher levels of physical activity or exercise interventions (18), especially when exercise is associated with weight loss. Fewer studies are available in cohorts with cancer, and as with leptin, the results are mixed. Theriau et al. (2016) showed that Conditional Media (CM) created from the adipose tissue of High Fat Diet (HFD)-fed animals caused an increase in the proliferation on MCF7 cells compared to cells exposed to CM prepared from the adipose of lean chow diet-fed counterparts (19). However, physical activity ameliorated these proliferative effects of HFD-CM on MCF7 cells, by increasing adipoR1 and p27T^{198} by AMPK, reducing pAktT^{308} in a manner that depended on the volume of physical activity exposure. High volumes of physical activity (> 3 km/day) completely abolished the adverse effects of HFD feeding on cancer cell proliferation (19).

Thus, evidence to date about ghrelin and adipokines and exercise in healthy cohorts or those with cancer/cachexia is incomplete and not consistent within or across species. No study to date has investigated the levels of adiponectin, leptin, and ghrelin in muscle, tumor, adipose tissue, and serum, simultaneously, in relation to exercise in either human or animal models of cancer cachexia. Therefore, the novelty of this study is assessing these cytokines at four sites and also measuring functional variables and determining the correlation between them. Therefore, the aim of this study was to investigate the effects of exercise training on cachexia and the major cytokines potentially linked to cancer cachexia: ghrelin, leptin, and adiponectin, in mice with breast cancer. It was hypothesized that six weeks of aerobic exercise training would maintain or improve body weight and muscle function, attenuate tumor growth rate, increase ghrelin, decrease leptin, and increase adiponectin in mice with mammary breast cancer, relative to sedentary control mice. It was further hypothesized that the improvement or maintenance in body weight and muscle function after exercise and the attenuation of tumor growth rate would be significantly related to these beneficial adaptations in ghrelin and cytokines.

2. Materials and Methods

This study was an animal experimental study, which was conducted at Tarbiat Modares University, Tehran, Iran.

2.1. Cell Line

The MC4-L2 cells that are Estrogen Receptor-positive (ER+) breast ductal carcinoma were used. The process of cell culture was done as reported previously (3, 20). The cells were cultured in T75 flask in DMEM/F-12 medium containing 100 μg/mL penicillin,15 mM HEPES, 100 μg/mL streptomycin, glutamine, and 10% Fetal Bovine Serum (FBS). By using 0.025% trypsin, the cells were detached from the bottom of flasks, and after rinsing with Phosphate Buffered Saline (PBS) and enzyme neutralization using 10% FBS, all content of the flask were emptied into Falcon tubes and centrifuged at 1200 rpm for four minutes. The supernatant was decanted and the cell plate dissolved in the medium containing 10% FBS. Hemocytometer and Trypan blue were used to determine cell count and cell viability, respectively.

2.2. Sample

Animals, purchased from the Pasteur Institute of Iran, were kept under 12-hour dark and light cycle, at temperature of 23 $\pm$ 2°C and suitable humidity, with free access to food and water. The sample size was selected on the basis of similar studies and statistician experts. For the Tumor sample, female BALB/c mice (n = 20) were anesthetized using a suitable dose of Ketamine and Xylazine, and then one million MC4-L2 cells were injected subcutaneously into the right upper thigh of each mouse. Healthy control female BALB/c mice (n = 10) were recruited for comparison of muscle endurance. This study was approved by the Animal Ethics Committee of Sport Sciences Research Institute, during year 2016. The registration number was IR.SSRI.REC.1395.129.

2.3. Study Design

The tumor sample (n = 20) was randomly divided to two groups: Tumor Control (TC) and Exercise group (E). The exercise group performed progressive aerobic training for six weeks. Prior to the initiation of the exercise training, the mice were exposed to treadmill familiarization for five days. Familiarization was done with gradually increasing speeds (10, 12, 14, 16, and 18 m/minute) at 0% inclination. Following the acclimation, the progressive aerobic training protocol began at 16 to 18 m/minute, 0% incline, 10 to 14 min/session, five days/week for five weeks (21). Weekly increases in running speed during the training period were used as a guide to assess adaptation to exercise training. No electrical stimulation was performed. The mice were encouraged to run by a gentle tap on the tail or hindquarters. The TC group was placed on a switched-off treadmill during the 5-week training period for the exact same time as the training group. The exercise group animals stopped training 48 hours before being sacrificed. All outcome testing was done by non-blinded assessors.

2.4. Food Intake, Body Weight and Tumor Volume and Weight Measurements

Food intake was estimated by subtracting residual weekly food weight/cage from initial food weight dispensed to each cage every week to the nearest 1.0 gm. All animals were weighed at baseline and weekly with a digital scale. Tumor size was measured in two dimensions, weekly, during six weeks. The larger tumor dimension was considered as length (L), and the other (at 90 degrees) as width (W). After appearance of the tumor, the length and width of the tumor were measured by a digital caliper once a week. Tumor volume was then estimated using the tumor volume formula: $[V = \pi/6 (W \times L2)]$. After sacrificing, the entire tumor and gastrocnemius muscle were dissected and the final tumor weight and gastrocnemius muscle were measured. The degree of precision for tumor and muscle weight was 0.0001 g.

2.5. Muscle Endurance Measurement (Kondziela's Inverted Screen Test)

Mice were placed in the center of the wire mesh screen, a stopwatch was started, and the screen was rotated to an inverted position over two seconds, with the mouse's head declining first. The screen was held steadily 40 to 50 cm above a padded surface. The time when the mouse fell off was noted, or the mouse was removed if the criterion time of 120 seconds was reached. The test was scored as paper of Deacon (22).

2.6. Blood and Tissue Sampling

The mice were euthanized 48 hours after the last exercise or sham exercise session. During the euthanasia period, blood (1.5 ml) was withdrawn. Blood samples were then centrifuged for 15 minutes at 4000 rpm, serum was collected and then serum and tissues were stored at -80 °C for further analysis.

2.7. Training Effectiveness

The Heart Weight to Body Weight (HW/BW) ratio was used as an indicator of the effectiveness of training (23). After sacrificing, the heart weight was measured and the ratio was calculated using the final body weight.

2.8. Cytokine Measurements

Serum and muscle, fat and tumor tissue were removed and frozen (-80°C) immediately after the mice were sacrificed. Fresh-frozen tissues (100 mg) were homogenized. The homogenates were immediately centrifuged at 12000 g for 20 minutes at 4°C, and the supernatant was removed as the detergent-soluble fraction. Protein concentrations were determined using the Bio-Rad Protein Assay with BSA for the standard curve. The samples were stored immediately in aliquots at -80°C for subsequent ELISA analysis. Assays of ghrelin (Code number RAB0207, Sigma Aldrich USA, Intra-Assay: CV < 10%, Inter-Assay: CV < 15%, Detection Range: 0.1 - 1,000 ng/mL), leptin (SEA084mu, cloud-clone corp. wuhan USA, Intra-Assay: CV < 10% Inter-Assay: CV < 12%, Detection Range: 0.156 to 10 ng/mL), and adiponectin (ab108785 Abcam USA, Intra-Assay: CV < 4.8% Inter-Assay: CV < 7.1%, Detection Range: 0.78 ng/mL to 50 ng/mL) were performed by ELISA kits. All assays were measured in duplicates and the mean was reported.

2.9. Statistical Analysis

All data are preented as mean ± Standard Deviation (SD) after ascertaining normality of distribution visually and statistically. Independent t-tests were used to assess the main effects of exercise training for outcomes measured only once at the conclusion of the study (tumor weight, heart weight, and heart weight/body weight ratio). Repeated measures Analysis of Variance (ANOVA) was used to assess the main effect of Time and Group x Time interaction for outcomes measured repeatedly across the experiment (body weight, food intake, muscle endurance, and tumor volume during six weeks, as well as cytokine levels). It should be noted that all repeated measurement assumptions were checked. When the Group x Time interaction was significant in the ANOVA model, post-hoc t tests of Bonferroni were used to ascertain the specific time points, at which the change over time differed between groups. Relationships between changes in variables of interest (e.g. change in adipokines and change in tumor size) were analyzed via linear regression models and Pearson correlation coefficient. All analyses were performed using the SPSS statistical software Ver. 19(IBM, Chicago, IL, USA) with the significance level set at P < 0.05.

3. Results

3.1. Body Weight and Food Intake

The mean body weight and food intake between the 2 tumor groups is shown in Table 1. Body weight did not differ significantly between TC and E groups across six weeks (P = 0.189). However, the E group had a significantly higher food intake than TC (P = 0.042). Unexpectedly, there was a negative correlation between food intake and body weight during the six weeks in TC (r = -0.93, P = 0.008), which was not seen in the E group (r = 0.68, P = 0.134).

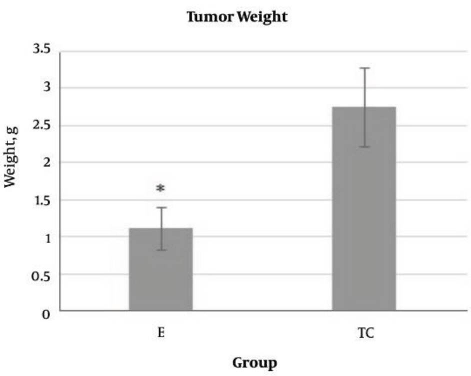
3.2. Muscle Weight

As expected, gastrocnemius muscle weight was higher in E (0.0787 ± 0.012 mg) compared to the TC group (0.045 ± 0.009 mg; P = 0.001) after sacrificing at six weeks. The mean difference between the two groups for muscle weight was 0.033 mg (CI: 0.016, 0.045).

3.3. Tumor Size and Tumor Weight

As hypothesized, the final tumor weight after sacrifice was significantly lower in the E group compared to the TC group (P = 0.001), Figure 1. The mean difference between the 2 groups for tumor size was 1.625 g (CI: 0.064, 2.33). Consistent with this finding, the rate of tumor growth was attenuated in the E group compared to the TC group over six weeks (P = 0.001, ES = 0.78). This E effect was not observed at week 1 (P = 0.63; mean diff 2.55g CI: -8.77, 25.25) or week 2 (P = 0.24; mean diff 27.92g CI: -30.99, 144.82), yet the 2 groups were significantly different from week 3 to 6 (week 3: P = 0.001; mean diff 166.99g, CI:73.35, 345.49; week 4: P = 0.001; mean diff 326.33g, CI:14.45, 576.58; week 5: P = 0.001; mean diff 777g, CI:141.5, 1317.51; week 6: P = 0.001; mean diff 1327g, CI:302.22, 1945.22).

Figure 1. Comparison of Tumor Weight (g) Between Exercise (E) and Tomur Control (TC) Groups



*P < 0.001.

Table 1. Body Weight and Food Intake Throughout the Study Period Between the Groups[a,b]

	Group	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
Body weight, g	TC	17.83 ± 0.98	18.03 ± 0.91	18.60 ± 1.12	19.05 ± 1.03	19.66 ± 1.07	20.81 ± 1.22
	E	17.75 ± 0.69	17.98 ± 0.77	18.26 ± 0.83	18.61 ± 0.78	19.72 ± 1.03	19.93 ± 1.23
Food intake, g	TC	165.50	166.05	162.82	160.23	155.04	140.62
	E	162.90	169.5	166.84	167.33	170.55	172.04

Abbreviations: TC, Tumor Control; E, Exercise; g, grams
[a]Data are presented as Means ± Standard deviation
[b]Food intake was measured for the whole cage of each group and therefore has only a single mean value for each group.

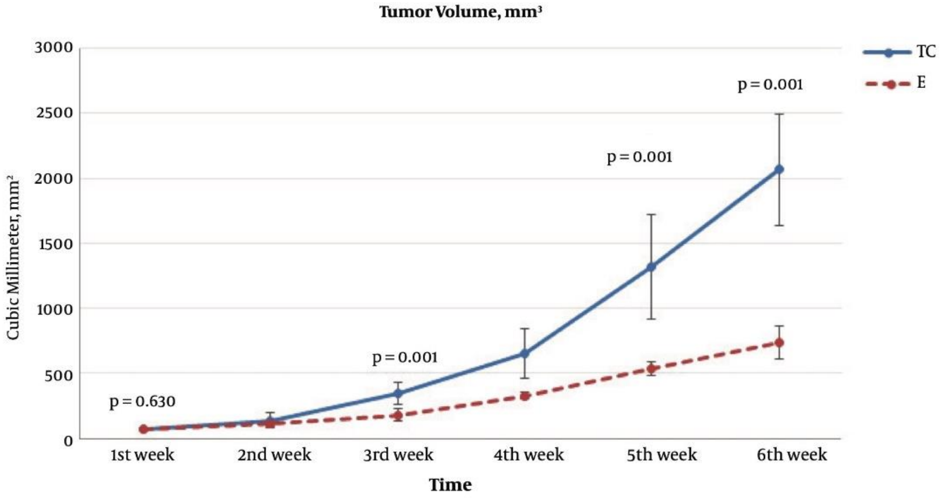


Figure 2. Tumor Volume (mm^3) Between Exercise (E) and Control (TC) Groups

3.4. Muscle Endurance Test

Kondziela's inverted screen test was used to determine muscle endurance of the mice in the healthy control, TC, and E groups. Healthy mice held on for more than 120 seconds on the device. There was a significant difference among the three groups (P = 0.001) overall. There were significant differences among all three groups from week 3 to 6. The healthy group was the strongest group and E was stronger than TC, Figure 3.

3.5. Fitness Adaptations

The heart weight to body weight (HW/BW) ratio is an index of efficiency of training (23), with higher ratios indicating better training adaptation. The HW/BW ratio was higher in E (0.006 ± 0.001) than in the TC group (0.004 ± 0.001; P = 0.001), as expected. The mean difference between the 2 groups for HW/BW ratio was 0.002 (95% CI: 0.001, 0.003). The correlation between HW/BW ratio and muscle weight and tumor weight was r = 0.736 (P = 0.001) and r = -0.663 (P = 0.005), respectively. The relationship between HW/BW ratio and the endurance test at the sixth week was r = 0.621 (P = 0.010).

3.6. Adipocytokine Changes

Adiponectin: As hypothesized, serum adiponectin was higher in E than TC at the end of the trial (P = 0.001). Similarly, fat adiponectin was higher in E than TC (P = 0.002), as was muscle adiponectin (P = 0.014). However, tumor adiponectin was similar between the two groups (P = 0.47), Table 2.

Leptin: As hypothesized, leptin was significantly lower in E compared to TC in serum, fat, muscle, and tumor, Table

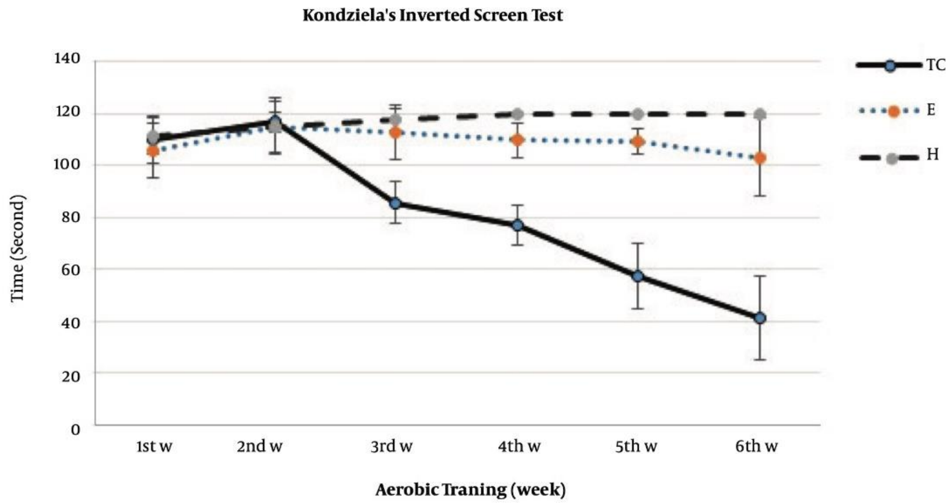


Figure 3. The Result of Kondziela's Inverted Screen Test (sec) Between the Groups (TC: Tumor Control, E exercise, H Healthy)

2.

Ghrelin: Ghrelin was only measured in serum and tumor, and results were mixed, Table 2. It was significantly higher in serum in the E compared to the TC group, as hypothesized, yet lower in E than TC in presence of tumor.

Table 2. Levels of Adiponectin, Leptin and Ghrelin in Tissues Between the Groups[a]

Adipocytokine	TC	E	P Value
Adiponectin, pg/ml			
Serum	7.91 ± 1.46	12.16 ± 2.21	0.001
Tumor	35.91 ± 2.41	36.92 ± 3.09	0.471
Fat	23.16 ± 2.38	30.56 ± 4.86	0.002
Muscle	25.21 ± 2.71	29.57 ± 3.47	0.014
Leptin, ng/ml			
Serum	3.42 ± 0.38	2.15 ± 0.11	0.001
Tumor	3.67 ± 0.67	2.95 ± 0.32	0.016
Fat	10.41 ± 1.11	5.02 ± 1.14	0.001
Muscle	6.20 ± 2.33	3.91 ± 1.21	0.027
Ghrelin, pg/ml			
Serum	1454.40 ± 18.12	1526.41 ± 32.11	0.001
Tumor	1122.20 ± 100.80	1028.11 ± 50.31	0.033

Abbreviation: TC, Tumor Control; pg, picogram; ng, nanogram; ml, milliliter; E, Exercise

[a]Data are presented as Means ± Standard deviation

[b]ANOVA test, $P < 0.05$ was considered significant.

3.7. Associations Between Adipokines and Other Variables

Data from E and TC groups were pooled to analyze these relationships. There were inverse associations between leptin and adiponectin in tumor (r = -0.846 P = 0.008), serum (r = -0.754 P = 0.031), muscle (r = -0.607 P = 0.110), and adipose tissue (r = -0.892 P = 0.003), as expected. This study also investigated the relationship between these factors and the outcomes related to cancer progression and cachexia.

3.8. Tumor Size

As hypothesized, tumor size was directly related to leptin in serum (r = 0.94, P = 0.001), adipose tissue (r = 0.83, P = 0.001), and tumor (r = 0.59, P = 0.016). Similarly, tumor weight was directly related to leptin level in serum (r = 0.78, P = 0.001) and adipose tissue (r = 0.87, P = 0.001), as expected. Also, as hypothesized, tumor size (r = -0.67, P = 0.004) and tumor weight (r = -0.87, P = 0.001) were both inversely related to serum ghrelin. By contrast, tumor size was directly related to tumor ghrelin (r = 0.72, P = 0.002).

3.9. Body Composition

There was a significant positive relationship between leptin and body weight in adipose tissue (r = 0.557, P = 0.025) and serum (r = 0.512, P = 0.043), yet not in muscle (r = 0.468, P = 0.068) or tumor (r = 0.173, P = 0.523). As expected, muscle weight was inversely related to tumor (r =

-0.56, P = 0.025), serum (r = -0.84, P = 0.001) and adipose tissue (r = -0.72, P = 0.002) leptin levels, and positively related to serum ghrelin (r = 0.81, P = 0.001).

3.10. Fitness

As expected, the HW/BW ratio (aerobic fitness index) was inversely related to leptin in tumor (r = -0.42, P = 0.109), serum (-0.63, P = 0.008), muscle (r = -0.62, P = 0.010), and adipose tissue (r = -0.61, P = 0.013). Also, as anticipated, muscle endurance was inversely related to leptin in tumor (r = -0.62, P = 0.009), serum (-0.82, P = 0.001), and adipose tissue (r = -0.87, P = 0.001), and directly related to ghrelin in serum (r = 0.78, P = 0.001).

There were no significant relationships between adiponectin and any of the above variables.

4. Discussion

As hypothesized, aerobic training significantly decreased both the growth rate and final weight of the tumor compared to non-exercising controls. Also, as hypothesized, exercising mice had greater food intake, muscle endurance, heart weight/body weight (fitness), and muscle weight than controls. In addition, many of the hypothesized potentially beneficial adaptations to exercise in cytokines were observed, including significantly increased adiponectin at all sites except the tumor, decreased leptin at all sites, and increased ghrelin in serum. Finally, as anticipated, the levels of cytokines after training predicted some of the beneficial physiological outcomes related to cancer cachexia noted above. Thus, the current data provides evidence for the beneficial effect of aerobic training in the modulation of cytokines involved in tumor cachexia and growth, resulting in attenuation of tumor burden, greater food intake, increased muscle size and endurance and better cardiovascular and musculoskeletal fitness in mice with breast cancer compared to non-exercising control mice with breast cancer.

4.1. Effect of Exercise on Cachexia and Cytokines

Cachexia is associated with loss of muscle mass as well as muscle function. On the 3rd week, muscle endurance declined as tumor volume increased, and both of these changes were attenuated by concomitant aerobic exercise compared to sedentary mice. For determine cachexia, advanced devices must be used to measure the composition of the mouse body, which was a limitation of the current study. Other positive adaptations to the exercise intervention included a higher food intake, HW/BW ratio, and gastrocnemius muscle size. Therefore, several common features of cancer cachexia in mice were mitigated by the aerobic training intervention.

The current results are in line with the results of several animal studies (3, 24), which have shown a reduction in tumor volume after aerobic training. Isanejad et al. (2016) and Khori et al. (2015) reported a reduction in tumor volume after aerobic training associated with changing levels of several miRNAs (miR-21, Let-7a and miR-206) linked to cachexia and their target genes (3, 25). Reduced tumor volume after exercise training in animals has also been associated with reduction in levels of angiogenic cytokines and inflammation products (20) within tumor tissue. In this study, for the first time, reduced tumor volume in the aerobic training group as well as modification of 3 cytokines influencing appetite and energy metabolism (leptin, ghrelin and adiponectin) were indicated. Notably, in the cases of ghrelin and leptin, these changes were associated with some of the features of cancer cachexia measured.

Ghrelin plays an autocrine/paracrine role in a number of processes associated with cancer development, including cell proliferation, cell migration, and apoptosis. A small number of studies have focused on ghrelin, specifically in the tumor tissue of cancer patients. Jeffrey et al. (2005) showed that ghrelin levels in breast cancer cells are higher than in normal cells, and ghrelin stimulates proliferation of cancer cells (26). In the present study, it was shown that aerobic training reduced the levels of ghrelin in tumor tissue, correlated with a reduction in tumor volume compared to sedentary tumor-bearing mice. Therefore, it is possible that reduced tumor growth with exercise may be related in part to reduced levels of ghrelin in tumor tissue.

By contrast, consistent with other studies, increased serum ghrelin levels were observed in the mice after aerobic training. Thus, it may be that serum ghrelin acts in a different manner to ghrelin in tumor tissue, preventing cachexia, and inhibiting tumor growth. Circulating ghrelin has a strong orexigenic effect (27). In tumor-bearing states, cachectic factors, such as cytokines, can elicit effects on energy homeostasis that mimic leptin and suppress orexigenic ghrelin. As shown in Table 1, food intake in the aerobic training group was higher than the control group. Although individual levels of food intake and serum ghrelin could not be correlated as food intake was measured for the group as a whole, the findings are consistent with the possibility that aerobic exercise stimulates food intake via increased circulating ghrelin. Ghrelin is known to inhibit leptin and pro-inflammatory cytokine expression by human monocytes and T cells (28), which could be one mechanism by which ghrelin increases appetite. Thus, a beneficial adaptation to exercise training in cancer cachexia may be modulation of ghrelin and other appetite-regulating neuropeptides.

Adiponectin and leptin are altered with adiposity and exert antagonistic effects on cancer cell proliferation.

Adipokines are bioactive particles that mediate metabolism, inflammation, angiogenesis, and proliferation. Leptin and adiponectin represent two adipokines that elicit generally opposing molecular effects. There are associations between increased serum leptin levels and increased tumor growth, while adiponectin exhibits an inverse, relatively strong correlation with cancer development. Leptin has been shown to increase proliferation, migration, and invasion of cancer cells (29), while lower plasma adiponectin levels are associated with larger tumor size and metastasis in clear-cell carcinoma of the kidney (30). Adiponectin can also antagonize the actions of leptin. For example, leptin phosphorylates and activates the signal transducer and activator of transcription (STAT)3 and STAT5 and Janus Kinase (JAK)2, which are involved in cancer development. By contrast, adiponectin can increase protein tyrosine phosphatase 1B (PTP1B), which then de-phosphorylates STAT3 and JAK2, thus antagonizing leptin signaling.

In this study, levels of serum adiponectin were higher and leptin levels were lower after exercise compared to non-exercising control mice, consistent with studies of physical activity in humans. Although normally secreted from adipose tissue, leptin can be secreted from breast cancer cells. Levels of leptin in tumor tissue and adipose tissue were significantly lower with exercise, yet levels of adiponectin were not different in tumor tissue and significantly higher in adipose tissue after exercise. It is possible that the exercise training suppressed leptin signaling and improved cachexia in this cancer model by increasing levels of adiponectin. However, as these regulatory factors were only measured at the end of training, it is not possible to ascertain the time course and causal relationships among them. These adaptations to training require further study with sequential sampling over the full time course of tumor growth and cachexia development.

In summary, ghrelin, leptin, and adiponectin can modify energy metabolism and appetite and may have important roles in cancer cachexia and tumor progression in both animals and humans. Aerobic training for six weeks in a murine model of breast cancer successfully attenuated tumor growth and cachexia, including food intake, body composition and muscle function/fitness compared to sedentary mice, and some of these benefits were related to beneficial cytokine/hormone adaptations in these animals. Future investigations of the time course and molecular mechanisms underlying these adaptations, optimal dose-response patterns, and relevance to human cohorts with breast and other cancers are warranted.

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Effects of nine weeks L-Carnitine supplementation on exercise performance, anaerobic power, and exercise-induced oxidative stress in resistance-trained males

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[Purpose] Studies of L-carnitine in healthy athletic populations have yielded equivocal results. Further scientific-based knowledge is needed to clarify the ability of L-carnitine to improve exercise capacity and expedite the recovery process by reducing oxidative stress. This study aimed to examine the 9-week effects of L-carnitine supplementation on exercise performance, anaerobic capacity, and exercise-induced oxidative stress markers in resistance-trained males.

[Methods] In a double-blind, randomized, and placebo-controlled treatment, 23 men (age, 25±2y; weight, 81.2±8.31 kg; body fat, 17.1±5.9%) ingested either a placebo (2 g/d, n=11) or L-carnitine (2 g/d, n=12) for 9 weeks in conjunction with resistance training. Primary outcome measurements were analyzed at baseline and at weeks 3, 6, and 9. Participants underwent a similar resistance training (4 d/w, upper/lower body split) for a 9-week period. Two-way ANOVA with repeated measures was used for statistical analysis.

[Results] There were significant increases in bench press lifting volume at wk-6 (146 kg, 95% CI 21.1, 272) and wk-9 (245 kg, 95% CI 127, 362) with L-carnitine. A similar trend was observed for leg press. In the L-carnitine group, at wk-9, there were significant increases in mean power (63.4 W, 95% CI 32.0, 94.8) and peak power (239 W, 95% CI 86.6, 392), reduction in post-exercise blood lactate levels (-1.60 mmol/L, 95% CI -2.44, -0.75) and beneficial changes in total antioxidant capacity (0.18 mmol/L, 95% CI 0.07, 0.28).

[Conclusion] L-carnitine supplementation enhances exercise performance while attenuating blood lactate and oxidative stress responses to resistance training.

[Key words] strength, lactate, antioxidant

INTRODUCTION

L-carnitine (LCR) is an endogenous compound synthesized in mammals from the essential amino acids lysine and methionine[1]. LCR is primarily stored in skeletal muscles and the heart at approximately 95%, while significantly lower concentrations are stored in the plasma[1]. From a physiological standpoint, LCR serves as a substrate for the enzyme carnitine palmitoyltransferase as well as the synthesis of acetyl-carnitine, which is necessary for maintaining a feasible pool of free coenzyme A (CoA), allowing for continuation of pyruvate dehydrogenase complex (PDC) and tricarboxylic acid cycle flux[2]. Theoretically, higher PDC flux during strenuous exercise would be expected to reduce blood lactate (BL) accumulation, which could potentially preserve glycogen stores and subsequently delay premature fatigue[3,4]. In addition, it is believed that LCR may reduce lactate production by maintaining the catalytic activity of the PDC through a buffering mechanism, thereby decreasing the acetyl-CoA/CoA ratio[5]. Siliprandi et al.[6] reported that LCR reduced lactate accumulation which was attributed to the constant acetyl CoA/CoA ratio and continuous flux of PDC.

As a potent anti-inflammatory compound, LCR has been shown to significantly reduce the levels of inflammatory markers such as interleukin-6 (IL-6) and tumor necrosis factor-α (TNF- α)[7] when used for long durations as a supplement; on the other hand, plasma levels of cytokines such as interleukin-1β (IL-1β), TNF-α, and IL-6 increase during and following intense prolonged exercise[8]. In particular, resistance training disrupts the balance between free radical production and the body's antioxidant defense system, resulting in a condition called exercise-induced immune dysfunction[9].

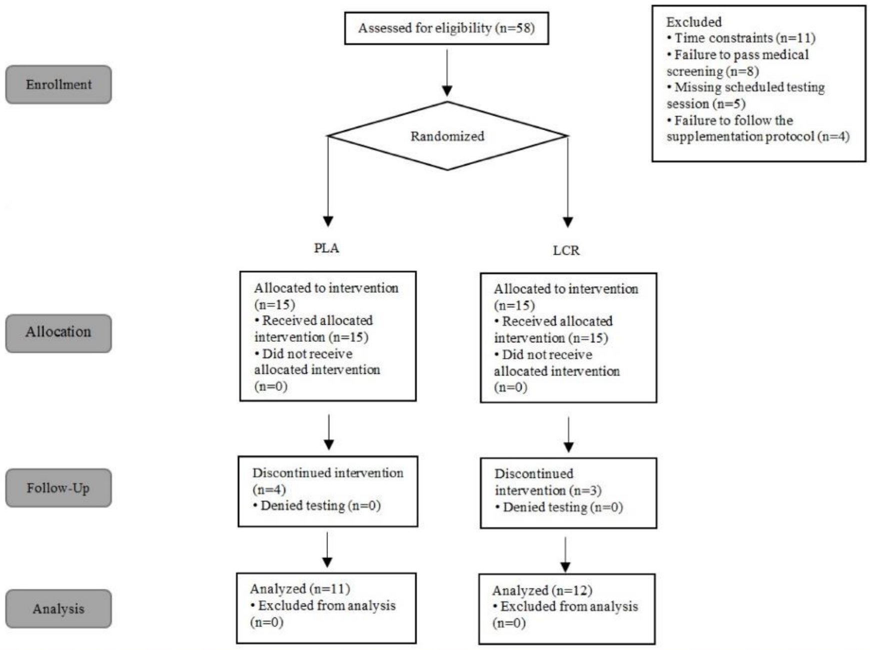

Figure 1. Consolidated standards of reporting trials diagram of study.

LCR can also act as an antioxidant during recovery from exercise, thereby mitigating oxidative stress, which may then decrease exercise-induced muscle damage. Guzel et al.[10] showed that 3 g of acute LCR supplementation increased glutathione and nitrate-nitrite levels identified as antioxidant markers after exhaustive exercise in young soccer players. Synergistic LCR supplementations with dietary choline and carnitine for a 21-d period has been shown to lower lipid peroxidation and promote conservation of retinol and α-tocopherol in healthy women before and after mild exercise[11]. Furthermore, 2 g/d of L-carnitine L-tartrate (LCLT) supplementation for 3 wk attenuated exercise-induced plasma markers of purine catabolism and circulating cytosolic proteins[12]. Magnetic resonance image scans in the same study indicated that muscle disruption in LCLT group was only 41-45% of the placebo area. LCLT supplementation appeared to mediate quicker recovery from hypoxic exercise[13]. Broad et al.[14] found that 2 g/d of LCLT supplementation for 2 wk suppressed the plasma ammonia response, an indicator of metabolic stress, to exercise in non-vegetarian active men. Additionally, it was found that LCLT supplementation reduced muscle oxygenation responses to resistance training and attenuated plasma malondialdehyde (MDA), a marker of membrane damage[15]. Despite the popularity of resistance training and increased exercise-induced muscle damage, little attention has been paid to the potential benefits of LCR when combined with resistance training and whether it might improve exercise performance by reducing muscle damage markers. Therefore, the purpose of this study was to investigate the effects of 9-wk LCR supplementation on exercise performance, anaerobic performance, and exercise-induced oxidative stress in resistance-trained males. We hypothesized that, in comparison with PLA, supplementation with LCR would provide greater gains in strength, enhance anaerobic capacity, and improve recovery following a resistance training program.

METHODS

Participants

A diagram of the study enrollment is illustrated as a CONSORT (Fig. 1). Twenty-three men volunteered from Tarbiat Modares University and the local surrounding community to participate in this 9-wk study. Inclusion criteria were as follows: good health, aged 18-40 y, body fat percentage 10-25%, and at least one year of regular resistance training including bench press and leg press/squats. Exclusion criteria were current smoking habit or use of nutritional supplements, and any problems that might affect their ability to perform resistance training. Physical activity levels were determined using standardized questionnaires adapted from the Stanford Usual Activity Questionnaire, Baecke Physical Activity Questionnaire, Kent State University, and Eastern Michigan University at

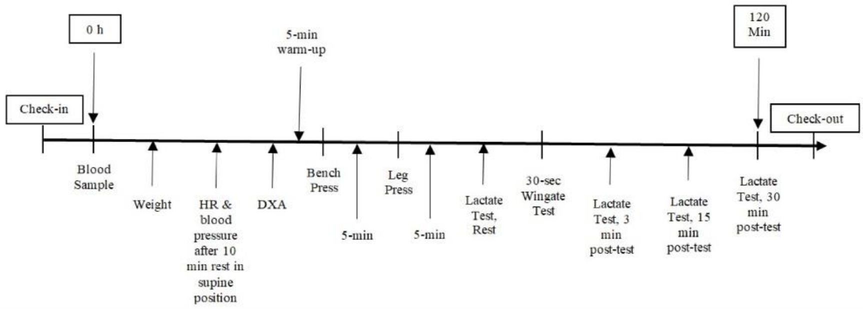

Figure 2. Presents the testing sequence timeline at baseline and weeks 3, 6, and 9.

baseline and wk 3, 6, and 9. In the familiarization session, testing procedures and potential risks and benefits associated with the study were verbally explained in detail. Participants then provided written informed consent prior to participation in accordance with the guidelines established by the Institutional Review Board at Tarbiat Modares University (approval #: 7RT-0258).

Experimental design

A placebo-controlled, double-blind design was used to conduct this study. All the testing was conducted in the exercise physiology laboratory at Tarbiat Modares University. Participants were matched into either the PLA or LCR group based on body mass, age, and resistance training experience. During the familiarization session and following informed consent, a research nutritionist and a professional strength and conditioning specialist met with each participant and explained in detail the strength training regimen as well as the nutritional and supplement requirements for the study period.

Testing sessions

The timeline of the testing protocol is presented in Fig. 2. The study included testing at baseline and at wk 3, 6, and 9, at which time blood samples were obtained, and body composition, exercise performance tests, and a series of BL tests were performed. Participants were instructed to refrain from strenuous exercise for 48 h and to have fasted for at least 12 h prior to each testing session.

Stength assessment

In the familiarization session, upper and lower body muscular strength was assessed using an isotonic bench press and leg press (Pullum Power Sports, Luton, United Kingdom) to determine the 1-repetition maximum (1RM). The 1RM was determined following a standard warm-up including 10 repetitions using 50% of participants' estimated 1RM, 5 repetitions using 70% of their estimated 1RM, and 1 repetition using 90% of their estimated 1RM. Weight was added until the 1RMs were determined. Verbal encouragement was provided during the test to ensure maximal effort. In the testing sessions, participants initially performed a general warm-up of ~5 min of light activity involving all muscles to be tested. Next, using the 1RM that was determined in the familiarization session, participants performed 3 sets of bench and leg press tests. For the first and second sets, participants performed 10 repetitions at 70% of 1RM on the bench press and leg press interspersed by 2 min of rest between sets and 5 min of recovery between each exercise. During the third set, participants were asked to complete as many repetitions as possible. Total lifting volume was calculated by multiplying the lifted weight times the number of completed repetitions. Test-retest reliability of performing upper and lower body strength assessments in our laboratory on resistance-trained participants showed low day-to-day mean coefficients of variation (CVs) and high reliability for the bench press (5.2%, intraclass, r=0.98) and leg press (7.4%, intraclass, r=0.97).

Anaerobic capacity assessment

Participants underwent a Wingate test on a computerized Lode Sport Cycle Ergometer (Lode BV, Groningen, The Netherlands) equipped with toe clips at a standardized torque factor of 0.7. The torque factor was set based on the manufacturer's guidelines relative to the population being tested. The seat position, seat height, handlebar position, and handlebar height were determined during familiarization sessions and repeated for all testing sessions. Participants were instructed to begin pedaling 10 s prior to application of the workload and continue at an all-out maximal capacity for the 30-s Wingate test. Test-retest reliability of performing Wingate test on participants in our laboratory yielded low day-to-day mean CVs and high reliability for absolute peak power (9.3%, intraclass, r=0.95) and mean power (7.6%, intraclass, r=0.94).

Body composition

Body composition was determined by dual energy X-ray absorptiometry (DXA) (*Lunar Prodigy; General Electric, Waukesha, WI*). Quality control calibration and scanning procedures were conducted as previously described[16]. All participants were scanned in the morning in a fasted state. Mean test-retest reliability studies performed on male athletes in our lab with the DXA machine yielded low mean CVs for total bone mineral content and total fat-free/soft tissue mass of 0.31–0.45% with a mean intraclass correlation of 0.985.

Blood lactate

BL levels were analyzed from finger prick capillary blood samples (*Analox GM7 Lactate Analyzer; Analox, Hammersmith, UK*). The analyzer device was calibrated using a standard control solution before each testing session. BL was measured 5 min prior to and immediately after the Wingate test and at 3, 15, and 30 min. The test-to-test reliability of conducting BL tests in our laboratory on resistance-trained males indicated low day-to-day mean CV and high reliability (5.2%, intraclass, r=0.89).

Resting heart rate & blood pressure

Resting heart rate (RHR) was measured after 10 min of rest in the supine position using standard procedures[17]. Then, systolic blood pressure (SBP) and diastolic blood pressure (DBP) were determined by auscultation of the brachial artery and a mercurial sphygmomanometer, based on standard clinical procedures[17].

Blood collection

Venous blood samples of approximately 10 mL were drawn after fasting for 12 h at the beginning of each testing session. Samples were collected from the antecubital vein in two 7.5-mL collection tubes utilizing a standard vacutainer apparatus. Blood samples were kept at room temperature for 15 min and then centrifuged at 3500 rpm for 10 min. The serum supernatant was removed and stored at -80°C in polypropylene microcentrifuge tubes for later analysis.

Serum clinical chemistry analyses

Laboratory measures were conducted at baseline, and weeks 3, 6, and 9. The tests included total and free carnitine, total antioxidant capacity (TAC), MDA, glutathione peroxidase (GPx), superoxide dismutase (SOD), catalase (CAT), IL-6, and TNF-α. All blood samples were analyzed in a biochemistry laboratory located at Tarbiat Modares University in Tehran, Iran. Day-to-day variability of the oxidative stress markers in our lab yielded a CV range of 0.06-0.23 and an intraclass correlation coefficient range of 0.67-0.90.

Supplementation protocol and dietary monitoring

Using a randomization code in a double-blind, placebo-controlled manner, participants in both the LCR and PLA groups were orally administered either 2 g/d-1 of LCR (Sina Nutrition, Inc., Tehran, Iran) or PLA (maltodextrin) for a 9-wk period. Both the LCR and PLA supplements were in the form of identical-looking ingestible capsules. Participants were instructed to consume 1 capsule with breakfast and 1 capsule with lunch (1 g per serving). The use of this dose has been shown to be safe and efficacious in previous studies[13,18,19]. Supplementation began ~30 min after the baseline testing session and continued throughout the 9-wk period. Compliance to the supplementation protocol was monitored by the research dietician who contacted participants on a weekly basis by phone. Participants were also asked to return all empty containers to the testing sessions at wk 3, 6, and 9, which allowed study personnel to assess compliance with the protocol.

Participants were instructed to maintain their current dietary intake throughout the study. In addition, they were given instructions during the familiarization session on how to record portion sizes and quantities. Participants completed a 3-day food recall (i.e., 2 weekdays and 1 weekend day) 1 week before all testing sessions. Dietary records were analyzed for total kilocalories, carbohydrate, protein, and fat using the NutraBase IV Clinical Edition (*CyberSoft, Inc., Phoenix, AZ*).

Resistance training protocol

Participants in both the PLA and LCR groups completed a 4-day/week resistance training program previously described in detail[20]. The weekly training volume was the same between the LCR and PLA groups. Briefly, the protocol involved training the upper and lower body twice per week using a 4-day split (i.e., upper body1, lower body1, upper body2, lower body2). The training program was composed of 15 exercises, including bench press, lat pull-down, shoulder press, seated row, dips, pullover, biceps curl, triceps press down, leg press, leg extension, leg curl, back extension, half squat, standing calf raise, and stiff leg deadlift. For each exercise, participants performed 3-6 sets of 8-15 repetitions with as much weight as they could while maintaining a proper form.

Further, participants maintained their training intensity between 70-85% of 1RM throughout the study. Rest periods between exercises were 1-2 min. Two certified strength and conditioning specialists supervised all lifts and showed participants how to record training data (i.e., lifts performed, reps, amount of weight lifted, etc.). Training was performed at 3 different training facilities, recorded in training logs, and signed off by selected fitness instructors to verify compliance. All 3 sports clubs used identical training equipment. Furthermore, at each testing session, participants were required to complete a physical activity questionnaire, describing their physical activity during the previous month.

Biochemical analyses

LCR fraction in all samples was analyzed by SRL Inc. (Tokyo, Japan). Total and free LCR levels were measured using an enzyme cycling method with an autoanalyzer (JCA-BM8000 series; JEOL, Tokyo, Japan)[21]. TAC was measured as previously described by Erel et al.[22] and reported in mmol/L. MDA was measured using the method described by Vassalle et al.[23] and expressed in μmol/L. GPx activity was measured using the method described by Bulucu et al.[24] and expressed in U/mL. SOD activity was measured as the inhibition of the rate of reduction of cytochrome c by the superoxide radical, observed at 550 nm as previously described by Berzosa et al.[25]; it was reported in μmol/mL. The CAT activity was measured in hemolysates as described by Aebi et al.[26]. and reported in nmol/mL. Serum TNF-α and IL-6 levels were measured by enzyme-linked immunosorbent assay (ELISA) technique as previously described by Arican et al.[27]. TNF-α and IL-6 activities were reported in pg/mL.

Adverse events

Study-related side effects were assessed using a questionnaire completed at each study visit. Participants reported how well they tolerated the supplement, how well participants followed the supplementation protocol, and whether participants encountered any medical issues and/or adverse symptoms throughout the study. The questionnaire consisted of the following 13 supplement-related symptoms: abdominal or stomach cramps, diarrhea, headache, nausea or vomiting, abdominal discomfort, body odor, depression, dizziness, impaired vision, loss of appetite or weight, swelling in hands or lower legs and feet, tingling sensation, and weakness. The options for each symptom were not at all, somewhat, moderately, very much, or extremely. Participants were asked to rank the frequency and severity of their symptoms during the supplementation period.

Statistical analysis

Data were analyzed using two-way ANOVA with repeated measures, evaluating for between-group differences as well as changes from baseline in body composition, HR and blood pressure, exercise performance, and blood markers. Data were considered statistically significant when the probability of error was 0.05. Data are presented as mean ± SD or mean change ± 95% CI as appropriate.

RESULTS

Participant demographics

The demographic characteristics of the groups are presented in Table 1. Thirty male participants were initially recruited for the study. Of these, 7 participants withdrew from the study due to personal reasons, and 3 were excluded due to low compliance (<80%) to the supplement. Therefore, a total of 23 participants completed the study. Characteristics of the study participants are presented in Table 1.

Dietary analysis, supplement & training compliance, and reported side effects

Food logs were used to measure the average daily caloric and macronutrient intake (Table 2). No significant difference in total calorie, protein, fat, and carbohydrate intake was observed among groups ($p>0.05$). Furthermore, subjective assessment of the physical activity evaluations indicated that none of the participants had any prominent changes in their level of physical activity throughout the 9 wk.

Table 1. Baseline characteristics of the study participants.

	Group	Mean
Age (y)	PLA	24.5 ± 1.5
	LCR	25.5 ± 1.5
Height (cm)	PLA	170.4 ± 5.8
	LCR	171.3 ± 3.1
Weight (kg)	PLA	77.9 ± 6.8
	LCR	84.1 ± 8.7
Body mass index	PLA	26.6 ± 3.4
	LCR	28.7 ± 3.5
Body fat (%)	PLA	16.1 ± 5.7
	LCR	18.0 ± 6.0
Resting HR (b/min)	PLA	57.0 ± 5.5
	LCR	60.5 ± 7.8
Resting SBP (mmHg)	PLA	116.1 ± 5.9
	LCR	114.5 ± 5.3
Resting DBP (mmHg)	PLA	77.2 ± 3.9
	LCR	74.0 ± 5.3

Values are means ± standard deviations. Data for the PLA (n= 11) and LCR (n=12) groups were analyzed by one-way ANOVA.

Body composition

Body composition data is shown in Table 2. No significant differences were observed between groups for the components of body composition (Wilks' Lambda group p=0.31, time p=0.02, and group x time p=0.06). Univariate analysis indicated that LCR supplementation did not influence body weight, fat mass, or fat-free mass compared to the PLA group ($p>0.05$).

Perfomance assessment: Muscular strength

Bench press. Results for all exercise performance variables are presented in Table 3. The analysis did not reveal a significant interaction effect between groups in the bench press performance ($p>0.05$). However, the analysis using baseline values as a covariate and evaluation of the mean change and 95% CIs of the 1RM upper body strength data demonstrated a significant increase in bench press performance (Fig. 3 A & B). The number of reps significantly increased at week 6 only in the LCR group (2.00 n, 95% CI, 0.39, 3.60) but not in the PLA group (0.90 n, 95% CI -0.77, 2.59). For week 9, the bench press reps assessment was as follows: LCR (3.41 n, 95% CI 1.96, 4.87), PLA (1.45 n, 95% CI -0.06, 2.97). A significant change in the bench press third set lifting volume at week 6 was observed in the LCR group (146 kg, 95% CI 21.1, 272) but not in the PLA group (65.2 kg, 95% CI -65.7, 196). For week 9, the bench press third set lifting volume was as follows: LCR (245 kg, 95% CI 127, 362), PLA (117 kg, 95% CI -5.64, 239). The percent changes from baseline in BP reps and third set lifting volume were both 27.5% for the LCR group.

Leg press. The number of leg press reps increased in the LCR group compared to the PLA group (p=0.01). In addition, the leg press third set lifting volume increased in the LCR compared to the PLA group (p=0.01). The analysis of mean changes with 95% CIs demonstrated significant differences in lower body performance between

Table 2. Dietary and anthropometric characteristics of study participants

	Group	Week 0 Mean ± SD	Week 3 Mean ± SD	Week 6 Mean ± SD	Week 9 Mean ± SD		p-level
Diet Characteristics							
Energy Intake (kcals/day)	PLA	2,116 ± 718	2,147 ± 723	2,250 ± 546	2,000 ± 311	G x T	0.48
	LCR	2,449 ± 529	2,414 ± 490	2,457 ± 549	2,444 ± 439		
Protein (g)	PLA	145.9 ± 38.5	151.9 ± 44.2	153.6 ± 44.0	156.4 ± 59.3	G x T	0.57
	LCR	147.7 ± 37.4	156.3 ± 39.1	157.1 ± 38.2	162.9 ± 46.1		
Fat (g)	PLA	74.4 ± 36.7	72.2 ± 35.3	73.5 ± 33.1	74.2 ± 26.0	G x T	0.73
	LCR	93.4 ± 32.1	98.8 ± 28.3	96.2 ± 22.8	95.0 ± 25.7		
Carbohydrate (g)	PLA	198.9 ± 68.1	202.0 ± 50.3	218.2 ± 70.2	185.1 ± 32.1	G x T	0.46
	LCR	258.5 ± 106.0	231.2 ± 81.2	240.7 ± 91.0	218.9 ± 61.0		
Anthropometry							
Body Weight (kg)	PLA	77.9 ± 7.09	78.1 ± 7.12	77.6 ± 7.26	78.1 ± 7.36	G x T	0.10
	LCR	84.3 ± 8.98	84.5 ± 8.78	84.3 ± 8.85	83.7 ± 8.92		
Fat Mass (kg)	PLA	12.1 ± 5.05	12.2 ± 5.29	12.0 ± 5.34	12.2 ± 5.14	G x T	0.15
	LCR	14.8 ± 5.26	15.1 ± 4.94	14.5 ± 4.73	14.2 ± 4.74		
Fat-Free Mass (kg)	PLA	54.1 ± 2.70	54.2 ± 2.70	54.0 ± 2.67	54.2 ± 2.63	G x T	0.06
	LCR	56.2 ± 2.78	56.3 ± 2.67	56.1 ± 2.56	56.8 ± 2.70		

Values are means ± standard deviations. Dietary intake data were analyzed by two-way ANOVA with repeated measures. Greenhouse-Geisser group (G), time (T), and group x time (G x T) interaction p-levels are reported with univariate treatment p-levels. The analysis revealed the overall Wilks' Lambda group (p=0.17), time (p=0.07), and group x time (p=0.44) effects.

Table 3. Exercise performance characteristics of study participants

	Group	Week 0 Mean ± SD	Week 3 Mean ± SD	Week 6 Mean ± SD	Week 9 Mean ± SD		p-level
Bench Press Repetitions (n)	PLA	12.0 ± 3.3	12.3 ± 2.9	12.9 ± 3.4	13.4 ± 3.2	G x T	0.08
	LCR	14.1 ± 4.0	14.2 ± 4.2	16.1 ± 3.8	17.5 ± 4.1		
Bench Press third Set Lifting Volume (kg)	PLA	1,042 ± 374	1,075 ± 335	1,107 ± 321	1,159 ± 333	G x T	0.17
	LCR	1,005 ± 315	1,012 ± 311	1,152 ± 296	1,250 ± 306		
Leg Press Repetitions (n)	PLA	22.7 ± 8.32	24.4 ± 9.16	24.3 ± 7.7	23.8 ± 9.0	G x T	0.01
	LCR	26.0 ± 6.92	28.4 ± 8.79	31.0 ± 7.4	34.6 ± 7.59		
Leg Press third Set Lifting Volume (kg)	PLA	9,032 ± 3,556	9,665 ± 3,784	9,788 ± 4,036	9,364 ± 3,733	G x T	0.01
	LCR	8,662 ± 3,553	9,440 ± 4,062	10,145 ± 3,210	10,836 ± 3,835		
Wingate Mean Power (Watts)	PLA	545 ± 85	524 ± 76	553 ± 75	540 ± 92	G x T	0.08
	LCR	545 ± 85	553 ± 133	586 ± 120	624 ± 120		
Wingate Peak Power (Watts)	PLA	1,639 ± 303	1,580 ± 345	1,633 ± 388	1,595 ± 441	G x T	0.03
	LCR	1,712 ± 363	1,751 ± 329	1,755 ± 302	1,952 ± 424		
Wingate Absolute Peak Power (Watts)	PLA	21.2 ± 4.97	20.4 ± 5.34	21.1 ± 5.28	20.6 ± 6.51	G x T	0.04
	LCR	20.5 ± 4.70	20.9 ± 4.48	20.8 ± 4.02	23.2 ± 5.20		
Wingate Relative Peak Power (Watts/kg)	PLA	7.00 ± 0.82	6.73 ± 1.03	7.13 ± 0.74	6.91 ± 0.92	G x T	0.10
	LCR	6.78 ± 1.92	7.67 ± 2.02	7.95 ± 1.87	8.49 ± 1.82		

Values are means ± standard deviations. Bench press, leg press, and cycling performance data were analyzed by two-way ANOVA with repeated measures. Greenhouse-Geisser group (G), time (T), and group x time (G x T) interaction p-levels are reported with univariate treatment p-levels. The analysis revealed the overall Wilks' Lambda group (p=0.03), time (p<0.0001), and group x time (p=0.02) effects.

groups (Fig. 3 C & D). The change in leg press reps from baseline to week 6 was as follows: LCR (5.00 n, 95% CI, 1.67, 8.32), PLA (1.63 n, 95% CI, -1.83, 5.10). The change in leg press reps at week 9 was as follows: LCR (8.58 n, 95% CI 5.09, 12.06), PLA (1.09 n, 95% CI -2.54, 4.73).

Comparisons at week 3 demonstrated a significant increase in leg press third set lifting volume in the LCR group (777 kg, 95% CI, 32.3, 1523) but not in the PLA group (633 kg, 95% CI -145, 1,411). There was a significant mean change from baseline to week 6 in the LCR group (1,483 kg, 95% CI 416, 2,549) but not in the PLA group (756 kg, 95% CI -357, 1,870). A significant improvement was observed at week 9 only in the LCR group (2,683 kg, 95% CI 1,591, 3,774) but not in the PLA group (331 kg, 95% CI -808, 1,471). The percent changes from baseline in LP reps and third set lifting volume in the LCR group were 38.1% and 30.2%, respectively.

Anaerobic power

The analysis revealed significant interaction effects for peak power (p=0.03) and absolute peak power (p=0.04) between groups, but no significant interaction effect in mean power or relative peak power (p>0.05) between groups. The analysis of mean changes with 95% CIs indicated significant differences in anaerobic performance

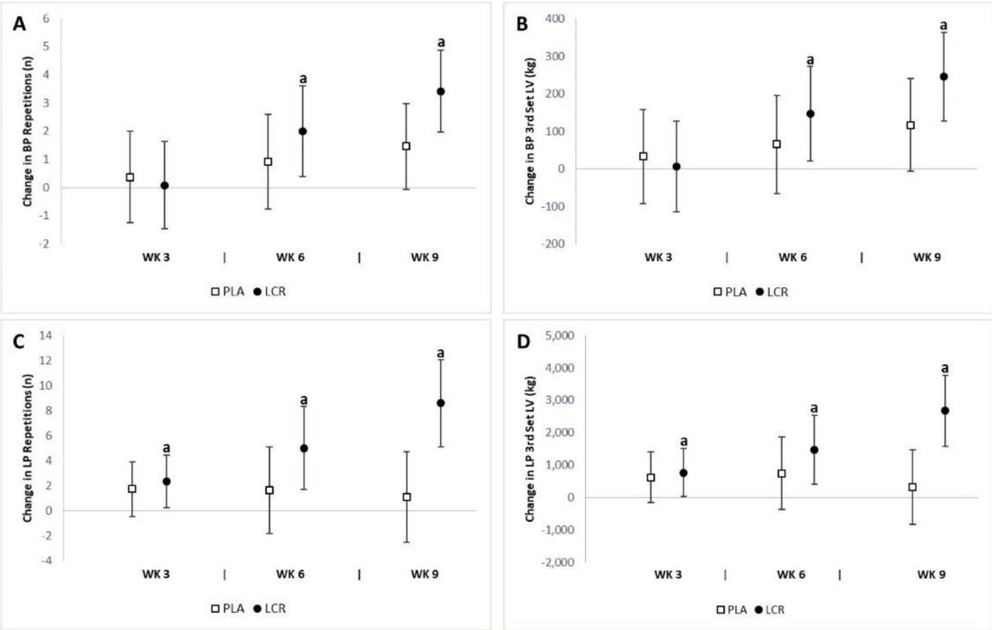

Figure 3. Change in strength performance for the placebo (PLA) and L-carnitine (LCR) treatments at baseline and weeks 3, 6, and 9. Panels A & B represent the change in bench press (BP) repetitions and third set lifting volume (LV), respectively. Panels C & D represent change in leg press (LP) repetitions and third set lifting volume, respectively. (a) denotes a statistically significant change from baseline (p<0.05). Values are the mean change ± 95% confidence interval.

between groups (Fig. 4). There was a significant improvement in mean power at week 9 in the LCR group (63.4 Watts, 95% CI 32.0, 94.8) but not in the PLA group (-5.24 Watts, 95% CI -38.0, 27.5). A significant change in peak power at week 9 was observed in the LCR group (239 Watts, 95% CI 86.6, 392) but not in the PLA group (-43.5 Watts, 95% CI -203, 116); the significant change in absolute peak power at week 9 was also observed in the LCR group (2.78 Watt/kg, 95% CI 0.99, 4.57) but not in the PLA group (-0.59 Watt/kg, 95% CI -2.46, 1.27). A significant change in relative power at week 9 was observed in the LCR group (0.70 Watt/kg, 95% CI 0.33, 1.08) but not in the PLA group (-0.08 Watt/kg, 95% CI -0.47, 0.30). In the LCR group, the percent changes from baseline in mean power, peak power, absolute peak power, and relative peak power were 12.8%, 14.8%, 12.5%, and 14.1%, respectively.

Total and free l-carnitine assessment

We observed significant differences between groups in both the total (p=0.005) and free (p=0.003) LCR levels. The analysis of mean changes with 95% CI's indicated significant changes in total and free LCR levels between groups (Fig. 5). Significant mean changes from baseline in total plasma LCR levels at week 6 were seen in the LCR group (6.02 µmol/L, 95% CI 2.42, 9.63) but not in the PLA group (0.33 µmol/L, 95% CI -3.43, 4.09). A significant increase in total plasma LCR levels at week 9 was observed in the LCR group (8.35 µmol/L, 95% CI 5.53, 11.1) and not in the PLA group (0.45 µmol/L, 95% CI -2.48, 3.40). Significant mean changes from baseline in free plasma LCR levels at week 6 were seen in the LCR group (4.59 µmol/L, 95% CI 1.62, 7.56) but not in the PLA group (-0.19 µmol/L, 95% CI -3.29, 2.90). Furthermore, free plasma LCR levels at week 9 were higher in the LCR group (7.04 µmol/L, 95% CI 3.74, 10.3) than in the PLA group (0.13 µmol/L, 95% CI -3.31, 3.57). The percent changes from baseline in total and free plasma LCR levels for the LCR group were 15.7% and 14.9%, respectively.

Blood lactate & oxidative stress assessment

Table 4 presents the pre- and post-exercise BL assessments. The analysis revealed significant interaction effects for 3-min (p=0.04), 15-min (p=0.01), and 30-min (p=0.04) post-exercise BL levels. The analysis of mean changes with 95% CIs demonstrated significant changes in post-exercise BL levels between groups (Fig. 6). A significant decrease in 3-min post-exercise BL at week 9 was observed in the LCR group (-1.84 mmol/l, 95% CI -2.97, -0.90) and not in the PLA group (-0.17 mmol/L, 95% CI -1.15, 0.81). Significant mean changes from baseline in

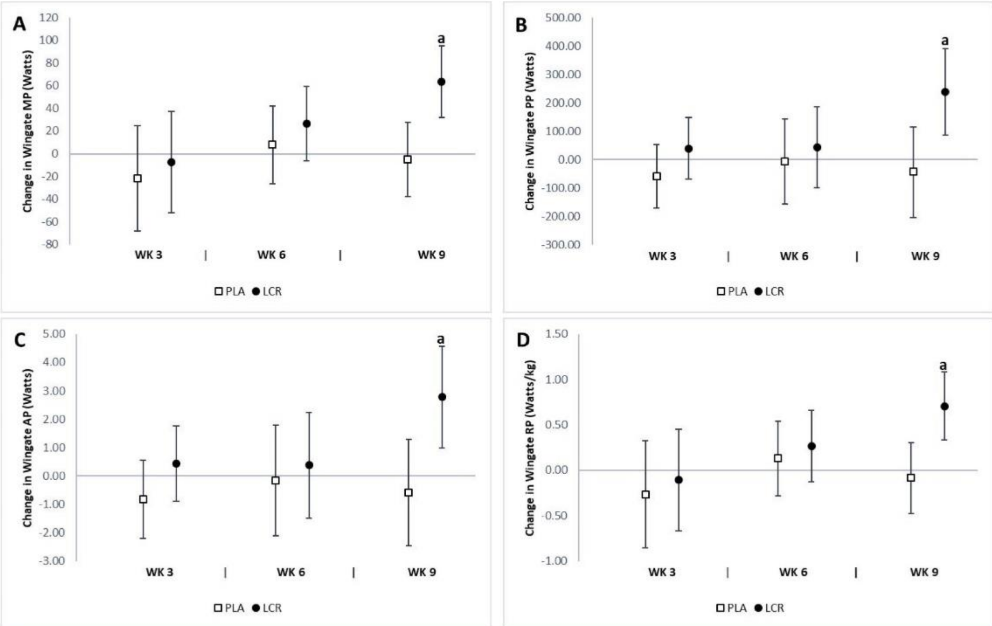

Figure 4. Change in cycling test performance for the placebo (PLA) and L-carnitine (LCR) treatments at baseline and weeks 3, 6, and 9. Panels A, B, C, and D represent the change from baseline in mean power (MP), peak power (PP), absolute peak power (AP), and relative peak power (RP), respectively. (a) denotes statistically significant change from baseline ($p<0.05$). Values are mean change ±95% confidence interval.

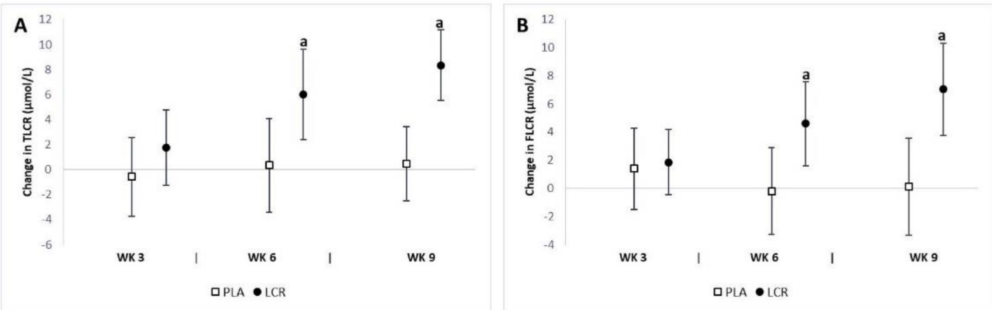

Figure 5. Change in plasma LCR levels for the placebo (PLA) and L-carnitine (LCR) treatments at baseline and weeks 3, 6, and 9. Panels A and B represent the total LCR (TLCR) and free LCR (FLCR) levels, respectively. (a) denotes a statistically significant change from baseline ($p<0.05$). Values are mean change ± 95% confidence interval.

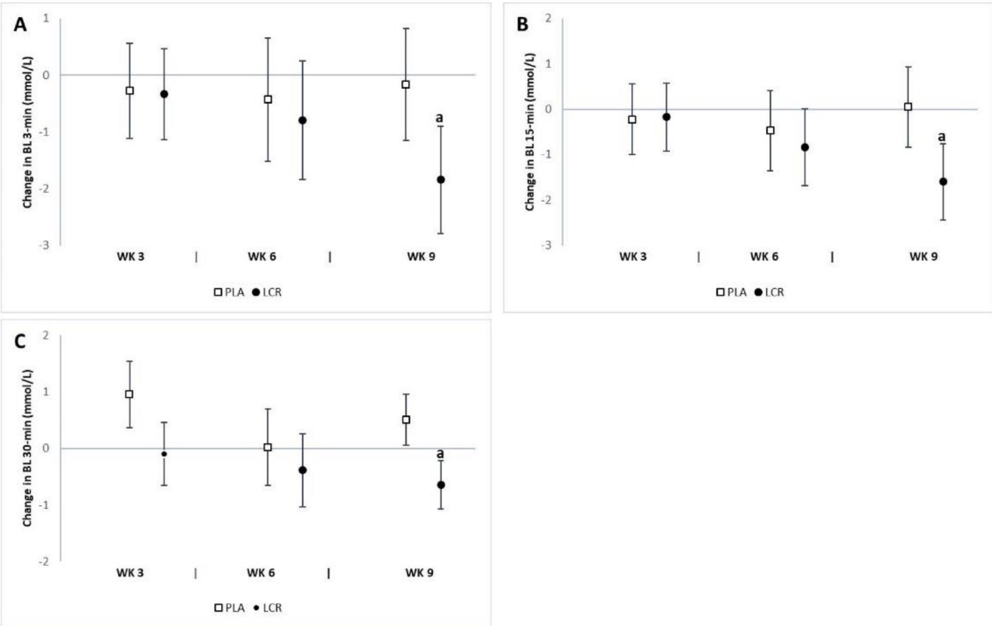

Figure 6. Change in post-exercise blood lactate (BL) levels for the placebo (PLA) and L-carnitine (LCR) treatments at baseline and weeks 3, 6, and 9. Panels A, B, and C represent post-exercise BL levels at minutes 3, 15, and 30, respectively. (a) denotes a statistically significant change from baseline (p<0.05). Values are mean change ± 95% confidence interval.

Table 4. Post-exercise blood lactate and oxidative stress characteristics of the study participants.

	Group	Time (wk) Week 0 Mean ± SD	Week 3 Mean ± SD	Week 6 Mean ± SD	Week 9 Mean ± SD		p-level
Blood Lactate							
3-min post-Wingate test ($mmol/L^{-1}$)	PLA	10.7 ± 1.19	10.4 ± 1.47	10.2 ± 1.93	10.5 ± 2.04	G x T	0.04
	LCR	10.1 ± 0.99	9.80 ± 0.91	9.34 ± 1.46	8.29 ± 0.56		
15-min post-Wingate test ($mmol/L^{-1}$)	PLA	10.7 ± 1.06	10.5 ± 1.64	10.3 ± 1.25	10.8 ± 1.24	G x T	0.01
	LCR	9.87 ± 1.49	9.70 ± 0.89	9.03 ± 0.92	8.27 ± 0.71		
30-min post-Wingate test ($mmol/L^{-1}$)	PLA	5.73 ± 1.14	6.69 ± 0.98	5.75 ± 1.14	6.24 ± 1.25	G x T	0.04
	LCR	4.60 ± 0.97	4.51 ± 0.96	4.22 ± 1.27	3.96 ± 0.99		
Oxidative Stress							
TAC (mmol/L)	PLA	1.45 ± 0.22	1.41 ± 0.16	1.46 ± 0.19	1.43 ± 0.16	G x T	0.02
	LCR	1.49 ± 0.13	1.60 ± 0.10	1.66 ± 0.15	1.77 ± 0.14		
MDA (μmol/L)	PLA	0.64 ± 0.13	0.63 ± 0.18	0.62 ± 0.10	0.66 ± 0.14	G x T	0.02
	LCR	0.56 ± 0.15	0.47 ± 0.09	0.48 ± 0.16	0.31 ± 0.18		
GPx (U/mL)	PLA	11.9 ± 2.15	12.1 ± 2.21	11.9 ± 1.81	11.4 ± 2.05	G x T	0.03
	LCR	11.7 ± 2.23	12.1 ± 1.92	12.2 ± 1.50	13.5 ± 1.73		

Values are means ± standard deviations. Oxidative stress data were analyzed by two-way ANOVA with repeated measures. Greenhouse-Geisser group (G), time (T), and group x time (G x T) interaction p-levels are reported with univariate treatment p-levels. The analysis revealed the overall Wilks' Lambda group (p=0.056), time (p=0.003), and group x time (p=0.004) effects.

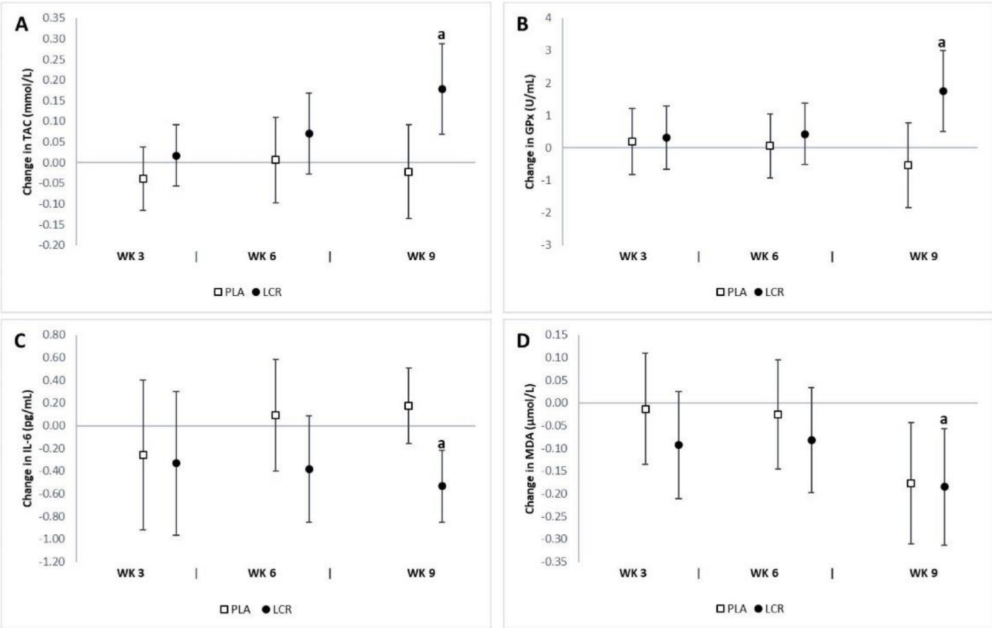

Figure 7. Change in oxidative stress status for the placebo (PLA) and L-carnitine (LCR) treatments at baseline and weeks 3, 6, and 9. Panels A, B, C, and D represent total antioxidant capacity (TAC), glutathione peroxidase (GPx), interleukin-6 (IL-6), and malondialdehyde (MDA), respectively. (a) denotes a statistically significant change from baseline (p<0.05). Values are mean change ±95% confidence interval.

15-min post-exercise BL at week 9 were seen in the LCR group (-1.60 mmol/L, 95% CI -2.44, -0.75) but not in the PLA group (0.04 mmol/l, 95% CI -0.83, 0.92). The mean change in 30-min post-exercise BL from baseline to week 9 was as follows: LCR (-0.64 mmol/L, 95% CI -1.07, -0.21), PLA (0.50 mmol/l, 95% CI 0.54, 0.95). The percent change from baseline at 3-min post-exercise BL level was as follows: LCR (-17.2%) and PLA (-1.46%); at min-15: LCR (-14.8%) and PLA (0.89%); and at min-30: LCR (-13.6%) and PLA (9.54%).

The analysis revealed a significant interaction effect between groups in serum TAC (p=0.02), MDA (p=0.02), and GPx (p=0.03). We did not observe any significant difference in serum SOD, CAT, IL-6, or TNF-α levels between groups. The analysis of mean changes with 95% CIs demonstrated significant differences in oxidative stress biomarkers between groups (Fig. 7). There was a significant increase in serum TAC at week 9 in the LCR group (0.18 mmol/L, 95% CI 0.07, 0.28) but not in the PLA group (-0.02 mmol/L, 95% CI -0.13, 0.09). A significant increase was observed in serum GPx at week 9 in the LCR group (1.75 U/mL, 95% CI 0.49, 3.00) but not in the PLA group (-0.54 U/mL, 95% CI -1.85, 0.77). There was a significant decrease in serum IL-6 at week 9 in the LCR group (-0.53 pg/mL, 95% CI -0.85, -0.21) but not in the PLA group (0.17 pg/mL, 95% CI -0.15, 0.50). The percent changes from baseline in serum TAC and GPx for the LCR group were 11.5% and 17.4%, respectively.

DISCUSSION

The main finding of our study was a significant increase in the BP and LP lifting volume at week 6 and week 9 in the LCR group. In addition, we observed a significant increase in mean power and peak power during the Wingate test. We further examined the effects of LCR on the metabolic response to exercise and found a significant attenuation in BL and markers of post-exercise inflammation. Interestingly, the observed changes in strength findings became manifest at week 6, while the Wingate and metabolic responses became significant at week 9.

There are limited data regarding the underlying mechanisms of LCR supplementation in relation to enhanced muscle mass and strength[28]. Our results showed that LCR supplementation had no significant influence on muscle mass though it improved upper/lower body strength. The applied training program was previously reported to elicit myofibrillar protein synthesis and recruitment of fast-twitch motor units[20]; however, our results failed to report any significant difference in muscle mass between the experimental groups. This is in line with previous evidence indicating that despite a greater growth potential in type I fibers, hypertrophy response is limited compared to type II fibers[29]. Sawicka et al.[30] showed that 8 weeks of LCR supplementation combined with creatine, L-leucine, and vitamin D resulted in an increase in muscle mass and strength due to elevated activation of the mTOR pathway. However, once LCR was tested alone using the same dosage, but for a longer period (i.e., 24 wk), no significant effect was found. In the present study, the training volume was significantly higher in the LCR group versus the PLA group. This may be attributed to the nature of the training program with moderate intensity, wherein the oxidation of long chain fatty acids acts as the predominant source of energy and LCR could increase the fat oxidation rate, thereby preserving muscle glycogen stores (25).

We reported that there was a significant reduction in BL accumulation post-30-sec Wingate test. In agreement with this, Jacobs et al.[31] showed a reduced BL accumulation after only short (10-s) bouts of anaerobic tests where LCR was ingested in a single dosage. A longer duration of supplementation could be speculated to buffer hydrogen ions produced by lactic acid breakdown to a greater extent, resulting in less pronounced blood acidity[2,32]. In another attempt, Siliprandi et al.[6] investigated the effects of 2 g of LCR before high-intensity exercise and found a decrease in plasma lactate, which may have been due to increased stimulation of pyruvate dehydrogenase activity. In contrast, Barnett et al.[5] showed that LCR supplementation for 14 days had no significant effect on lactate accumulation following a high-intensity cycling performance, despite a significant increase in plasma free carnitine concentrations. The attenuation in BL concentrations after strenuous exercise combined with LCR supplementation appears to be primarily due to carnitine-mediated enhancement of PDC activation and flux. During exercise of this nature, when the use of the acetyl group via the Krebs cycle is exceeding its production by the PDC reaction, carnitine buffers against acetyl-CoA accumulation by making acetylcarnitine in an enzymatic reaction, thereby providing free Co-enzyme A to maintain the Krebs cycle flux[33].

L-carnitine is involved in the transportation of activated long-chain fatty acids from the cytosol into the mitochondrion and the buffering of acetyl-CoA[5]; therefore, LCR is essential for mitochondrial β-oxidation[34]. It has been hypothesized that the buffering action of LCR, which attenuates the acetyl-CoA/CoA ratio, may reduce lactic acid production by maintaining the catalytic activity of the PDC[5]. These conditions explain the impact of carnitine on lactic acid metabolism.

The findings of our study also demonstrated that chronic LCR supplementation (2 g/d) increased TAC and GPx markers while it decreased MDA levels. Since no significant changes were observed in dietary intake during the study period, the changes in these markers may be attributed to the antioxidant capacity of LCR. Recent studies have indicated that LCR administration may prevent exercise-induced oxidative stress by decreasing lipid peroxidation, scavenging oxygen radicals, and up-regulating the activities of antioxidant enzymes such as GPx, SOD, and CAT[10,35-37]. Lee et al.[19] indicated that LCR might exert antioxidant properties for exercise-induced oxidative stress. After 3 wk of LCLT supplementation (2 g/d LCR), plasma MDA returned to resting values by 15 min post-exercise in the LCLT group, whereas MDA remained significantly elevated above pre-exercise levels throughout 24 h of recovery in the PLA group. Another study assessed the effect of 2 wk of LCR supplementation (2 g/d) on oxidative stress in active, healthy young men. Results indicated increased TAC and decreased serum MDA in the LCR group compared to the PLA group[36]. Inflammatory responses induce the production of reactive oxygen species (ROS), which regulate the expression of proinflammatory cytokines such as IL-1, IL-6, and TNF-α and subsequently activate the nuclear transcription factor-κB (NF-κB) pathway[38,39]. NF-κB, as a transcriptional regulator of DNA, plays a crucial role in the expression of more than 200 genes involved in immune and inflammatory responses[40,41]. Some studies identified both continuous and high-intensity intermittent exercise protocols as a strong stimulus of NF-κB activation[42-44]. Previous studies have shown that supplementation with antioxidants such as LCR, glutathione, and astaxanthin may reduce the formation of ROS, resulting in inhibition of the NF-κB activation cascade[45-48].

Conclusion and practical applications

A strength of our study was the duration of the intervention. Supplementing for this length of time helped to delineate the treatment effects; although strength performance improved by week 6, prolonged supplementation was necessary to observe the effects on anaerobic performance. Moreover, our findings were further strengthened by the fact that we recruited participants with 1 year of training experience, thus minimizing any neurological training effects and enhancing the generalizability of our study to individuals engaged in resistance training across various athletic disciplines. Hence, our results add to the known body of literature as LCR has been well studied in endurance athletes, but less is known regarding its effects on those involved in resistance training. A limitation of our study was the absence of muscle biopsy, which could have provided additional data regarding intramuscular LCR levels as well as molecular and cellular responses, including proteins involved in the mTOR pathway. Another limitation was the lack of measuring the stress factors related to the hypothalamus-pituitary-adrenal axis such as corticosterone, which may have helped explain the possible neurophysiological impact of LCR supplementation. From a practical point of view, our results suggested that 2 g/d of LCR supplementation improved muscle strength and anaerobic performance while decreasing post-exercise BL levels and attenuating exercise-induced oxidative stress markers in resistance-trained athletes. However, all of the abovementioned changes occurred independently of any change in body composition or hemodynamic parameters.

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Multi Directional Repeated Sprint Is a Valid and Reliable Test for Assessment of Junior Handball Players

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The aim of the present study was to examine the validity and reliability of a 10 × (6 × 5 m) multi-directional repeated sprint ability test (RSM) in elite young team handball (TH) players. Participants were members of the Iranian national team ($n = 20$, age 16.4 ± 0.7 years, weight 82.5 ± 5.5 kg, height 184.8 ± 4.6 cm, body fat 15.4 ± 4.3%). The validity of RSM was tested against a 10 × (15 + 15 m) repeated sprint ability test (RSA), Yo-Yo Intermittent Recovery test Level 1 (Yo-Yo IR1), squat jump (SJ) and countermovement jump (CMJ). To test the reliability of RSM, the participants repeated the testing sessions of RSM and RSA 1 week later. Both RSA and RSM tests showed good to excellent reliability of the total time (TT), best time (BT), and weakest time (WT). The results of the correlation analysis showed significant inverse correlations between maximum aerobic capacity and TT in RSA ($r = -0.57$, $p \leq 0.05$) and RSM ($r = -0.76$, $p \leq 0.01$). There was also a significant inverse correlation between maximum aerobic capacity with fatigue index (FI) in RSA test ($r = -0.64$, $p \leq 0.01$) and in RSM test ($r = -0.53$, $p \leq 0.05$). BT, WT, and TT of RSA was largely-to-very largely correlated with BT ($r = 0.58$, $p \leq 0.01$), WT ($r = 0.62$, $p \leq 0.01$), and TT ($r = 0.65$, $p \leq 0.01$) of RSM. BT in RSM was also correlated with FI in RSM ($r = 0.88$, $p \leq 0.01$). In conclusion, based on the findings of the current study, the recently developed RSM test is a valid and reliable test and should be utilized for assessment of repeated sprint ability in handball players.

Keywords: exercise testing, muscle strength, speed, team sport, test-retest

INTRODUCTION

Exercise testing in handball includes a series of anthropometric and physiological measurements associated with performance in this team sport (Schwesig et al., 2017).The anthropometric and physiological characteristics of team handball (TH) players are relative to their position in the field and competitive level (Nikolaidis et al., 2015b). Elite handball players have significantly higher strength, speed, agility, and cardiovascular endurance than their less competitive counterparts (Mohamed et al., 2009; Nikolaidis and Ingebrigtsen, 2013). In addition, handball players possess a high level of aerobic and anaerobic fitness (Buchheit et al., 2009a,b; Souhail et al., 2010) and repeated sprint ability (RSA) (Okuno et al., 2013). RSA is the ability to run short distances at maximum intensity multiple times with incomplete recovery between sprints (Barbero et al., 2006).

Success in handball, similar to many intermittent team sports, is related to strength, power, speed, and ability to perform repeated high intensity sprints in various directions. Analysis of handball matches showed that 12% of the total game time comprised of sprinting and high intensity running (Chelly et al., 2011). The average duration of each run in a handball competition was 14.4 s with 19.5 s recovery between runs (Chelly et al., 2011). However, most sprints in handball are not performed in a direct line and often include one or multiple change of directions (COD) during defensive and offensive actions. These findings suggest that repeated multi direction sprint ability may be a key discriminating factor in handball performance.

RSA is shown to be related to the athletic performance including the 30 m sprint performance test (Gouthon et al., 2015). In addition, a significant correlation has been reported between anaerobic power with the best time (BT, i.e., the fastest trial among those consisting an RSA test) and total time (TT, i.e., the sum of times of all trials in an RSA test) of a RSA test (Gharbi et al., 2015). Anaerobic power of handball players was also correlated with the fatigue index (FI) during a RSA test (Gharbi et al., 2015). Regular RSA training has been shown to improve time in 10 m sprint, height in countermovement jump (CMJ) and speed of ball in jump shooting in handball players (Dello Iacono et al., 2016). Therefore, different variations of RSA could be utilized in training and assessment of athletic performance in TH players.

RSA protocols vary in the number of sprints, distance of each sprint, recovery between sprints, and the use of COD (Mokou et al., 2016). Independent from these variables, the main indices of an RSA test are BT, TT, and FI (Atkinson et al., 2003). Most RSA tests include multiple sprints in a straight line or with only one COD. Therefore, straight RSA tests may not be suitable for the assessment of athletic performance in sports that include multiple changes of directions during a real match.

Recently, a multi-directional RSA test (RSM) has been developed and examined for validity and reliability in basketball players (Padulo et al., 2016). RSM includes multiple sprints with lateral movements as well as straight line movements and has more face validity than the RSA test protocols for basketball and handball, as it has been shown that these team sports include a large number of lateral movements in addition to straight-line sprints (Taylor et al., 2017). Since anthropometric and physiologic characteristics of basketball players are not the same as handball players (Jiménez et al., 2009), the reliability and validity of RSM should be assessed with handball players. The aim of the present study was to examine the validity and reliability of an RSM test in elite young handball players.

MATERIALS AND METHODS

Study Design and Subjects

The design of the current study was a single group cross over in which participants completed two RSA and two RSM tests in random orders (**Figure 1**). Twenty handball players (age: 16.4 ± 0.7 years, sport experience 5.6 ± 2.7 years, weekly training volume 9 h) of the Iranian national team volunteered to participate in this study (**Table 1**). This study was carried out in accordance with the recommendations of the Iranian Handball Federation and National Olympic Committee of Iran. Participants' parents or guardians provided written informed consent. All procedures were in accordance with the Declaration of Helsinki. The protocol was approved by the Ethics Committee of the Iranian Handball Federation.

Measuring Protocol

To avoid the diurnal variation of performance, assessments were completed between 4:30 p.m. and 6:00 p.m. in ambient temperature of 25°C and relative humidity of 40% at the national training hall. To minimize the effect of familiarization on athletic performance, each participant completed two RSA and RSM trials 48 h prior to data collection. Participants' height and weight were measured using a standard stadiometer and a calibrated scale. Body fat (%) was estimated using bioelectrical impedance (InBody 220, Phymed, Korea).

The vertical displacement of participants during squat jump (SJ) and CMJ was evaluated using accelerometer MyotestTM (Myotest SA, Sion, Switzerland) which was valid and reliable equipment to assess jumping performance (Choukou et al., 2014). Two trials were performed for each test and the best score was recorded. One-minute break was allowed between trials and between SJ and CMJ. Both tests were performed with participants maintaining hands on their hips according to the protocol of Bosco and Rusko (1983).

Yo-Yo intermittent test level 1 and Bangsbo formula was used to assess the aerobic capacity of participants (Bangsbo et al., 2008). This test has been recommended as more sensitive measure of changes in performance than maximum oxygen uptake in team sports (Bangsbo et al., 2008) and has been used in handball (Hermassi et al., 2017b), soccer (Eniseler et al., 2017) and basketball (Padulo et al., 2016). Participants were running between two lines separated by 20 m continuously at an incremental pace, dictated by an audio signal, till exhaustion. This test differs from 20 m shuttle run test (Batista et al., 2017) as it includes a 10 s recovery after the completion of each 40 m.

Each testing session started with a 15 min warm-up including running at low-to-moderate intensity and dynamic stretching. The RSA test included ten 30 m sprints with one COD (i.e., 15 + 15 m) and 30 s passive recovery between trials (Padulo et al., 2016). The RSM test consisted of ten 30 m sprints with multiple CODs (**Figure 2**) and 30 s passive recovery between trials (Padulo et al., 2016). Weakest time (WT) was defined as the slowest time among trials. Each trial was recorded in the nearest 0.01 s using a pair of photocells (Newtest Oy, Oulu, Finland). FI of RSA and RSM (Atkinson et al., 2003) was calculated using the Fitzsimons' formula (Fitzsimons et al., 1993).

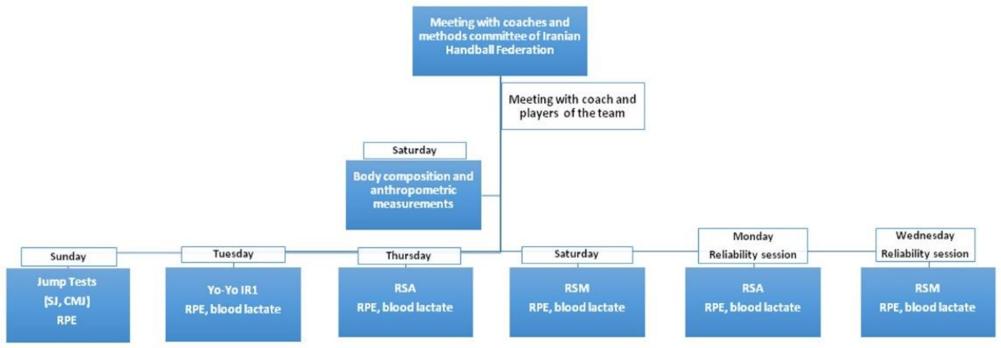

FIGURE 1 | Experimental design of the study. SJ, squat jump; CMJ, countermovement jump; RPE, rate of perceived exertion; Yo-Yo IR1, Yo-Yo intermittent recovery test level 1; RSA, repeated sprint ability test; RSM, multi-directional repeated sprint ability test.

TABLE 1 | Anthropometric characteristics, jumping performance and aerobic capacity of participants.

Parameter	Mean ± SD
Age (years)	16.4 ± 0.7
Body mass (kg)	82.5 ± 5.5
Height (cm)	184.8 ± 4.6
Body fat (%)	15.4%
VO_2max ($mL.min^{-1}.kg^{-1}$)	47.5 ± 2.8
RPE (a.u.)	9.3 ± 0.4
SJ (cm)	29.70 ± 4.89
CMJ (cm)	32.56 ± 4.54
RSM-lactate ($mmol.L^{-1}$)	10.50 ± 0.28
RSA-lactate ($mmol.L^{-1}$)	9.99 ± 0.15

SD, standard deviation; VO_2max, maximal oxygen uptake, estimated by covered distance in Yo-Yo IR1; RPE, rate of perceived exertion after Yo-Yo IR1; a.u., arbitrary units; SJ, squat jump; CMJ, countermovement jump; RSM, multidirectional repeated sprint ability test; RSA, straight-line repeated sprint ability test.

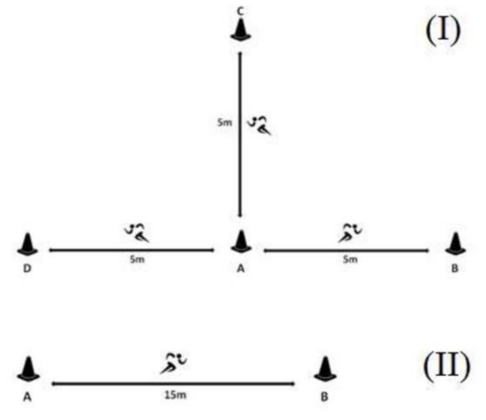

FIGURE 2 | Presentation of the RSM **(I)** and RSA test **(II)**. RSA, straight-line repeated sprint ability test; RSM, multi-directional repeated sprint ability test.

A drop of blood was collected from the index finger before and 3 min after each testing session to analyse the blood lactate concentration using a portable lactate monitor (Accusport Lactate Meter, Boehringer Mannheim®, and Germany). At the end of each testing session, participants rated the intensity of the testing session using the modified 10-points Borg scale (Foster et al., 2001). To allow sufficient recovery and prevent fatigue accumulation between testing sessions, there was a 48 h rest between each testing session.

Statistical Analysis

Data were analyzed using SPSS 24.0 (SPSS Inc., Chicago, IL). The probability level of statistical significance was set at $p \leq 0.05$ and descriptive statistics were expressed as means ± SE. Intra-class Correlation Coefficient (ICC) estimates and their 95% confident intervals were calculated based on a single-rating ($k = 1$), absolute-agreement, 2-way mixed-effects model (McGraw and Wong, 1996). Based on the 95%confident interval of the ICC estimate, values less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.90 are indicative of poor, moderate, good, and excellent reliability, respectively (Koo and Li, 2016). A will Hopkins Typical Error of Measurement, with Pearson's correlation were implemented to determine the agreement between measurements (Hopkins, 2016). To assess the size and direction of the linear relationship between BT, WT, TT, BLa, and FI, a bivariate Pearson's product-moment correlation coefficient (r) was calculated.

RESULTS

The anthropometric characteristics, jumping performance and aerobic capacity of participants can be seen in **Table 1**. The results of reliability measurements using ICC are presented in **Table 2**. According to the results, both RSA and RSM tests showed good to excellent reliability of the TT, BT and WT. In addition, the results of the agreement between the measurements of both RSA and RSM were analyzed using Will Hopkins Typical Error of Measurement and are presented in **Table 3**.

The results of the correlation analysis showed significant inverse correlations between maximum aerobic capacity and TT in RSA ($r = -0.57$, $p \leq 0.05$) and RSM ($r = -0.76$, $p \leq 0.01$). There was also a significant inverse correlation between maximum aerobic capacity with FI in RSA test ($r = -0.63$, $p \leq 0.01$) and in RSM test ($r = -0.62$, $p \leq 0.01$). In addition, the levels of lactate after RSA and RSM were correlated with maximum aerobic capacity ($r = 0.49$, $p \leq 0.05$) and ($r = 0.47$, $p \leq 0.05$) respectively. BT, WT, and TT of RSA were largely-to-very largely correlated with BT, WT, and TT of RSM (**Figure 3**, **Table 4**). TT in RSM correlated very largely with the Yo-Yo, but not with SJ and CMJ (**Figure 4**).

DISCUSSION

The main findings of the present study were that RSM indices showed a good reliability for both TT and FI and an excellent reliability for BT, WT, and RPE. These results indicate that RSM is a reliable test for the assessment of sprint ability with multiple COD s in youth handball players. TT, BT, WT, and BL showed a good reliability in RSA test. In addition, the reliability of FI and RPE were excellent in RSA test. These results indicate that RSA is a reliable test for assessment of afore-mentioned variables in youth handball players. The RPE levels in both RSA and RSM

TABLE 2 | Reliability of measurements in RSA and RSM using ICC.

		RSA				RSM			
		Mean ± SE	ICC	95% CI		Mean ± SE	ICC	95% CI	
TT (s)	Test	68.97 ± 0.23	0.83	0.57	0.93	112.17 ± 0.61	0.81	0.54	0.93
	Re-test	69.25 ± 0.24				112.59 ± 0.68			
BT (s)	Test	6.35 ± 0.08	0.88	0.70	0.95	9.99 ± 0.09	0.99	0.97	1.00
	Re-test	6.30 ± 0.08				1.02 ± 0.08			
WT (s)	Test	7.24 ± 0.07	0.82	0.54	0.93	11.86 ± 0.19	0.91	0.77	0.96
	Re-test	7.23 ± 0.08				11.97 ± 0.17			
FI (%)	Test	9.07 ± 1.15	0.99	0.97	1.00	12.34 ± 0.84	0.78	0.47	0.91
	Re-test	9.32 ± 1.06				11.44 ± 0.54			
Lactate ($mmol.L^{-1}$)	Test	9.99 ± 0.15	0.86	0.63	0.95	10.50 ± 0.28	−0.06	−1.34	0.56
	Re-test	9.77 ± 0.16				11.12 ± 0.22			
RPE (a.u.)	Test	8.80 ± 0.13	0.94	0.85	0.98	8.60 ± 0.12	0.93	0.82	0.97
	Re-test	8.76 ± 0.10				8.58 ± 0.12			

RSA, straight-line repeated sprint ability test; RSM, multidirectional repeated sprint ability test; ICC, intra-class correlation coefficient; TT, total time; BT, best time; WT, weakest time; FI, fatigue index; RPE, rate of perceived exertion.

TABLE 3 | Typical Error of Measurement and correlation of measurements in RSA and RSM using Will Hopkins reliability test.

		RSA				RSM			
		Estimate	Lower CL	Upper CL	*r*	Estimate	Lower CL	Upper CL	*r*
TT (s)	Raw units	0.74	0.56	1.09	0.72	2.04	1.54	3.01	0.69
	Standardized	0.96	0.53	2.23		1.06	0.58	2.67	
BT (s)	Raw units	0.23	0.17	0.34	0.79	0.08	0.06	0.011	0.98
	Standardized	0.78	0.45	1.61		0.19	0.12	0.32	
WT (s)	Raw units	0.23	0.17	0.33	0.69	0.48	0.36	0.70	0.83
	Standardized	1.05	0.57	2.62		0.66	0.39	1.26	
FI (%)	Raw units	1.09	0.83	1.62	0.98	2.66	2.01	3.93	0.72
	Standardized	0.21	0.13	0.35		0.96	0.53	2.23	
Lactate ($mmol.L^{-1}$)	Raw units	0.42	0.32	0.62	0.79	1.27	0.96	1.88	−0.03
	Standardized	0.78	0.45	1.60		29.96	2.19	1.88	
RPE (a.u.)	Raw units	0.25	0.19	0.37	0.91	0.29	0.22	0.43	0.86
	Standardized	0.44	0.27	0.77		0.60	0.35	1.10	

RSA, straight-line repeated sprint ability test; RSM, multidirectional repeated sprint ability test; TT, total time; BT, best time; WT; weakest time; FI, fatigue index; RPE, rate of perceived exertion.

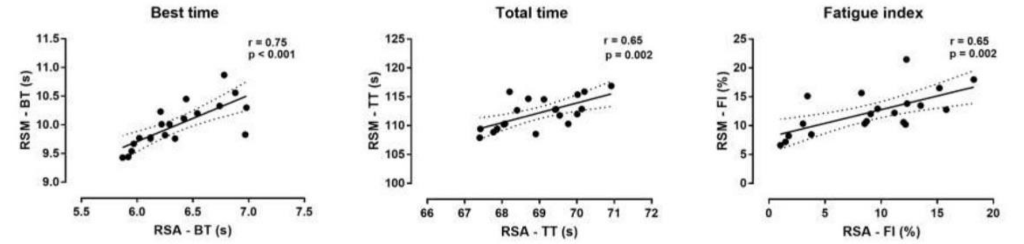

FIGURE 3 | Best time, total time and fatigue index in RSM and RSA. RSA, repeated sprint ability test; RSM, multi-directional repeated sprint ability test.

TABLE 4 | Correlations between RSM, RSA, jumping performance and aerobic capacity.

	RSM-BT	RSM-FI	RSA-TT	RSA-BT	RSA-FI	SJ	CMJ	Yo-Yo IR1
RSM-TT	0.660**	0.678**	0.648**	0.576**	0.754**	0.080	0.041	−0.756**
RSM-BT	–	0.880**	0.532*	0.750**	0.698**	−0.052	0.030	−0.615**
RSM-FI		–	0.518*	0.591**	0.653**	0.112	0.193	−0.529*
RSA-TT			–	0.664**	0.599**	0.208	0.233	−0.571**
RSA-BT				–	0.646**	0.077	0.108	−0.607**
RSA-FI					–	0.136	0.178	−0.641**
SJ						–	0.954**	−0.165
CMJ							–	−0.170

$^{*}p < 0.05$, $^{**}p < 0.01$; RSA, straight-line repeated sprint ability test; RSM, multidirectional repeated sprint ability test; TT, total time; BT, best time; FI, fatigue index; SJ, squat jump; CMJ, countermovement jump; Yo-Yo IR1, Yo-Yo intermittent recovery test level 1.

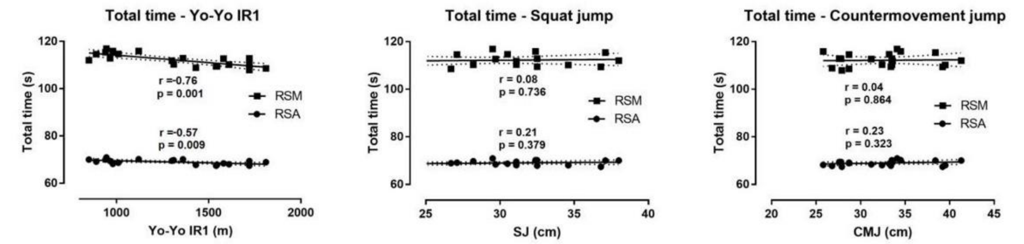

FIGURE 4 | Relationship of total time in RSM and RSA with jumping performance and aerobic capacity. SJ, squat jump; CMJ, countermovement jump; RPE, rate of perceived exertion; Yo-Yo IR1, Yo-Yo intermittent recovery test level 1; RSA, repeated sprint ability test; RSM, multi-directional repeated sprint ability test.

were similar and near maximal effort suggesting that athletes performed at the maximal level during both tests. The higher reliability of BT and WT in RSM compared to RSA suggest that strongest and weakest sprint performance of athletes are more consistent during RSM that RSA. Therefore, the BT and WT in RSM could be utilized to monitor RSA of elite handball players.

Previous researchers reported a poor reliability for FI when compared to BT and TT (Austin et al., 2013) and have questioned the use and the value of reporting FI in RSA (Oliver, 2009). The findings of the current study supported the claim that reliability of FI, calculated using the Fitzsimons' formula, may not be as strong as TT, BT, and WT in RSM. However, the reliability analysis of FI showed a good reliability in RSM and excellent reliability in RSA. Therefore, it appears that the value of FI in assessment of RSA may be subjective and perhaps specific to variables of a RSA test.

Performance in TT during RSA and RSM were significantly correlated with the maximum aerobic capacity that was assessed by a Yo-Yo test. The higher correlation of RSM with maximum aerobic capacity could be explained by the longer duration of the RSM test. The average TT in RSM was 112 s, twice as much as the duration of the RSA test. Therefore, athletes with higher maximum aerobic capacity could recover better during the sprints and achieve better results. This claim is supported by the significant inverse correlation of maximum aerobic capacity with FI in both RSA and RSM tests. Athletes with a higher maximum aerobic capacity showed quicker recovery between sprints and demonstrated lower FI and blood lactate level.

The results of BT, WT, and the TT of RSM trials were strongly correlated with the BT, WT and the TT of RSA tests. These strong correlations suggest that RSM test is as strong discriminator as RSA for assessing the athletics performance. Considering that RSM is a multi-direction test that stresses athletes' body for a longer period than RSA, it is possible that RSA performs better as a discriminating assessment for athlete selection, talent identification, and evaluation of a training intervention. On the contrary, RSM indices did not correlate with jumping ability, which was in disagreement with previous research showing low-to-moderate relationship between jumping tests and 10 × 20 m RSA test (Nikolaidis et al., 2015a). An explanation of this discrepancy might be the longer duration of RSM in the present study compared to the RSA protocol used in the abovementioned study.

Participants of the current study achieved the maximum aerobic capacity of 47.46 ± 2.76 $ml.kg^{-1}.min^{-1}$. This finding suggests that aerobic capacity of youth handball players were at the medium range and slightly above non-athletic populations. A previous study comparing handball players of different performance levels showed no difference for aerobic capacity, whereas the elite players had superior anaerobic power and jumping ability (Nikolaidis and Ingebrigtsen, 2013). Our findings were in agreement with previous studies (Malacko et al., 2013) and suggests that anaerobic energy system is a dominant energy system in TH and success in this sport may be more dependent on anaerobic glycolysis than maximum aerobic capacity.

Since the ability to perform movements in different directions and within short distance is unique in handball, the results of this study should be generalized with caution to other team sport with different characteristics. For instance, the RSM should also be tested by a future study for validity and reliability in soccer due to larger distances covered in-line. Strength of the study was that it confirmed the validity and reliability of the RSM which was developed initially in basketball (Padulo et al., 2016). Considering the popularity of handball, the findings of the present study are of great practical value for coaches and fitness trainers in the context of the training and testing of their players.

The present study established the validity and reliability of RSM test in handball; thus, coaches and fitness trainers are encouraged to use this test to monitor performance of their players. Two training strategies have been recommended to optimize RSA in handball players with the first one relying on the training specificity concept and the second one focusing on the main factors associated with this physical fitness component (Bishop et al., 2011). Accordingly, these strategies could apply in the case of RS; thus, training should include drills similar as RSM, e.g., 10 trials of 5 m distance multi-directional sprints with 30 s passive recovery. In addition, training should also include high-intensity intermittent aerobic exercises using COD similar as the exercises included in the Yo-Yo IR1 test, considering the large-to-very large correlations between all RSM indices and Yo-Yo IR1.

In conclusion, based on the findings of the current study, the novel RSM test is a valid and reliable test and should be utilized for assessment of RSA of handball players. So far, handball professionals use isokinetic strength of knee flexors and extensors, one repetition maximum of half squat, 5 m sprint test, agility and jump tests, Yo-Yo test and in-line RSA to monitor physical fitness (Hermassi et al., 2017a; Maurelli et al., 2017; Schwesig et al., 2017). We recommend the further use of the RSM in handball players in the context of a physical fitness battery administration.

AUTHOR CONTRIBUTIONS

AD conceived the idea of this paper and PN wrote the first draft. AD, MK, SA and MH participated in the organization of the experimental setting and the data collection. AD, DG, TR, and BK wrote the final draft. All coauthors approved the final version.

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